

Greenland Ice Sheet late-season melt: Investigating multi-scale drivers of K-transect events

Thomas J. Ballinger, Thomas L. Mote, Kyle Mattingly, Angela C. Bliss, Edward Hanna, Dirk van As, Melissa Prieto, Saeideh Gharehchahi, Xavier Fettweis, Brice Noël, Paul C.J.P. Smeets, Carleen H. Reijmer, Mads H. Ribergaard, and John Cappelen

Manuscript submitted on 19 December 2018, revised on 10 April 2019

Author Response

We thank Charalampos Charalampidis and two anonymous reviewers for offering constructive and thorough comments on our paper. Each concern is addressed below and in the manuscript, and we believe these changes have improved the clarity and quality of the paper. In particular, we have taken care to address common concerns amongst reviewers that involve clarification of the composite methodology (please see Section 3 “Methods”). We note that co-author Carleen H. Reijmer was inadvertently omitted from the author listing in the discussion paper and has been added accordingly.

Reviewer comments are shown in *italics* while author responses are subsequently provided in red.

1. Anonymous Reviewer #1

General Comments

In this study, Ballinger et al. investigate potential mesoscale and synoptic drivers of late season melt events in the K-transect sector of southwest Greenland. They find that synoptic scale processes are the primary driver, with late season K-transect melt events characterized by southerly flows of warm, moist air from lower latitudes onto the ice sheet. In contrast, local ocean-atmosphere interactions over Baffin Bay are not found to have any direct role in driving late season melt events.

This study provides novel and valuable insights into the variability of GrIS melt, identifying an important link between synoptic scale moisture transport and unseasonal melt events, which has not been previously explored. Overall, the analysis is well done and the manuscript is well written. My main concerns are: (i) the robustness of the results given the small number of years analyzed, (ii) lack of clarity regarding the initial hypothesis of marine layer forcing (what exactly would be expected if melt events were driven by marine layer forcing, and how do the actual results differ?), and (iii) potential issues with the interpretation of turbulent heat fluxes and associated arguments about the origin of warm, moist air that is transported from the south onto the GrIS. I discuss each of these below, along with other minor comments and suggestions for improvement.

We thank the reviewer for their comments and have addressed their concerns in our revision.

Specific Comments:

L32 “For the unseasonal melt period preceding the DOA”: Which unseasonal melt period? This seems to imply a sustained period of unseasonal melt before the DOA, whereas the unseasonal melt usually occurs in transient events. I suggest rephrasing as simply “For the period preceding the DOA”.

Thank you for the clarifying suggestion; we have made this change.

L40 “While thermal conduction and advection off south Baffin Bay open waters impact coastal air temperatures, consistent with previous studies”: Where is this shown in the manuscript?

Heat transfer off of ice-free ocean waters onto coastal areas is discussed at length in the second paragraph of the Introduction.

L47 “The Greenland Ice Sheet (GrIS) surface mass balance (SMB) decrease has contributed roughly 0.5 mm year⁻¹”: It’s the overall mass balance decrease (SMB + ice discharge) that has contributed 0.5 mm/year, not the SMB.

We have made this clarification in the manuscript.

L50 “west Greenland waters” -> “ocean waters west of Greenland”?

We have made the suggested change.

L83 “recent, temporally-anomalous GrIS late melt events spanning the end of summer to freeze-up of adjacent ocean waters”: Which recent events? Please provide a few examples and references.

We have slightly edited the text to reflect satellite era studies of late season GrIS melt in late boreal summer and autumn. Two papers referenced include Doyle et al., 2015 and Stroeve et al., 2017.

L112 and L156: Can you provide some further explanation as to why KAN_B was selected to build T+/T- composites, thus limiting the study period to only 5 years? Especially since the objective is to study melt events, why choose a station on the tundra instead of a station on the glacier? KAN_B has a much shorter data record than all the other K-transect stations, so the selected study period 2011-2015 is only a small sub set of the available data. With the short study period and with composites sub-divided into D_60 and D_30 bins, the D_30 composites comprise only 13 days of data. The next closest station, S5, has data going back to 2003, which would allow for a more robust analysis over a 13-year study period. If you repeat the analysis using S5 to build composites over 2003-2015, do the results shown in Figs. 3-6 and S4-S5 change very much? I think it would be preferable to use station S5 and the longer study period for these figures, or at least mention whether the KAN_B-based results are robust when S5 and the longer period are used. The only place I see a need for a shorter study period is in Table 2 and Fig. 2, where all the K-transect stations are compared over an overlapping period, but if

KAN_B were excluded then I think the overlapping period could still extend back to 2008 instead of 2011.

Our study provides a temporally homogenous examination of above-freezing temperatures along all current PROMICE and IMAU K-transect stations. The study spans 2011-2015 so that both networks of AWS observations can be included. We use above and below freezing air temperatures from Kan_B, located just off the ice edge, as bins for comparing atmospheric conditions about the transect. The intent is not to build the longest record of unseasonal melt conditions, but the most spatially complete.

L163: It would be helpful to summarize from Table 2 the frequency of T+ events at KAN_B (or S5, if it were used instead of KAN_B to build composites), and mention what percentage of days each represents, i.e., the D_60 bin has 69 events (~46% of days) and the D_30 bin has 13 events (~9% of days).

We have briefly summarized the frequency of T+ events from table 2 within the first paragraph of the methods.

L176 “IVT PR is then classified using the SOM technique to produce a matrix of moisture transport patterns, or nodes, that typically occur over the Greenland region”: This is very vague. Some additional description should be included for the benefit of readers who are not familiar with SOM - for example, mention that it is an unsupervised machine learning algorithm and that each daily IVT PR field is classified with its closest matching node from the SOM. Are the SOM dimensions and training parameters the same as in Mattingly et al. (2016), or is anything different? It’s not clear from this description. It would also be helpful to include in the Supplemental Materials a figure showing the SOM nodes and the wet/dry/neutral groups, so that readers have a better understanding of the SOM classification used in this study.

We have added some clarifying language in the last paragraph of the methods section on the SOM method and application of the Mattingly et al. (2016) SOM classification, from which we assess frequencies of wet, dry, and neutral IVT patterns as identified by the authors. We refer readers back to the aforementioned manuscript to view the SOM matrix referenced here.

L178 “As in Mattingly et al. (2016), similar wet (anomalously high), neutral (near climatological median values), and dry (anomalously low) IVT patterns are aggregated, then their frequencies are composited and tested following methods previously summarized”: What is meant by “tested” in this context? In the cited paper, the clustering of nodes into wet/dry/neutral groups was subjective, based on visual inspection. I don’t recall any testing of this grouping procedure.

The hypothesis tested is that the frequency of IVT patterns belonging to a given SOM node cluster (i.e. “wet” nodes) differs for T+ events compared to T- events. As you note, the grouping of nodes is based on visual inspection of the IVT patterns for each node, and the grouping procedure itself is not tested in this paper. We have edited the text to clarify this point.

L208-231 I find it difficult to follow the reasoning in these two paragraphs that leads to the conclusion that “late season melt inferred from T+ events may be driven by synoptic patterns as opposed to local marine forcing” (L234). Why exactly do we reject the hypothesis that local marine forcing drives the T+ events? Is it simply because the K-transect wind directions in T+ events are offshore instead of onshore? What about the other aspects discussed here – such as K-transect wind speeds, sensible and latent heat fluxes over ocean and GrIS, near surface winds in eastern Baffin Bay, etc. – how do they contribute to this argument? These paragraphs should be revised to clarify: if local marine forcing were driving the T+ events, then what would we expect the results here to look like? How do the actual results differ from that?

We have clarified a hypothesis of what physical dynamic and thermodynamic mechanisms would link Baffin Bay open water to GrIS melt in the last paragraph of the Introduction section.

L214-218 and Figures S4-S5: Sensible and latent heat fluxes in Figures S4 and S5 are described here as positive in the upward direction. Is this correct? I would have expected sensible heat fluxes over GrIS to be directed from the atmosphere to the ice sheet surface (i.e. negative SHF if the upward direction is positive). In particular, in the K-transect region during T+ events, if air temperature is greater than 0 C but the melting ice surface is at most 0 C, how can SHF be directed upward?

We have corrected the wording and the positive sensible and latent flux represents downward heat transfer by which the atmosphere heats the ocean and ice sheet.

L240 “In both T+ cases, low-level winds circulate poleward over north Labrador Sea areas of upward, turbulent heat flux (Figs. S4 and S5), aiding the heat and moisture transfer (as shown by heightened IVT values in T+ relative to T-) over western Greenland during D60 and D30 (Fig. 5)”: Following from my previous comment about the direction of SHF and LHF in Figures S4 and S5, I am wondering if turbulent fluxes over the north Labrador Sea are actually upward and if this region is actually the source of the heat and moisture transported onto western GrIS? Or do the heat and moisture originate from further south, around 30-35S? Subtropical origin seems more likely and is more consistent with the IVT fields shown in Figure 5.

We have corrected the sign as indicated in the previous comment. While the objective of this work is not to pinpoint origins of subpolar air masses traveling across the ice sheet, we suggest in the Discussions these air masses originate in deeper in the Atlantic than the domain resolved by our synoptic analyses. Upward turbulent heat fluxes (negative sign SHF and LHF in this analysis) over these remote areas may serve enhance the heat and moisture contributions to those air masses.

Of note, we have also changed D30 and D60 to [-30,-1] and [-60,-31], respectively, for consistency between text, figure, and table references to the time periods preceding Baffin Bay DOA.

L254 “higher 500 GPH values and on-ice lower tropospheric mean winds”: The phrasing here seems confusing. “Higher” refers to GPH being higher in T+ relative to T- events, but does “lower” refer to wind speeds in T+ relative to T-, or does it mean “lower troposphere”?

“Lower” refers to the troposphere and specifically the winds averaged over the 1000-700 hPa levels. We have clarified the corresponding language in the last paragraph of Results section 4.3.

L267 and Figure S6: Since each station-year is a separate data point, why not include all years of data for each station in Fig. S6 and related discussion? Only using the 2011-2015 period gives a very limited perspective on whether the temperatures are typically correlated or not, since we see statistically significant correlations in only three of five years.

We prefer to include a temporally homogenous correlation analysis of the nearby oceanic SSTs versus AWS air temperatures for the 2011-2015 period. Subsequent analyses may look to capture longer term local oceanic and coastal/ice sheet temperature linkages as well as the effects of the regional ice sheet-ocean pressure gradient in modulating onshore or offshore flows during T+ and T- periods.

Typographic Corrections and Figure/Table Formatting

Headers for sub-sections 2.2-2.4 should be in bold for consistency with the other headers.

We have made the suggested change.

Table 2: I find the labels here a bit confusing. Although each row is labelled as a relative measure (e.g., “S5 vs. KAN_B”), the columns “T+ n[-60, -31]” and “T+ n[-30, -1]” are not relative to KAN_B, they are the actual counts for each individual station.

We have clarified the language of the table to caption to more clearly describe the table contents.

Figures 2 and 6: It’s difficult to distinguish between the dark and light red/blue colors in the bar charts.

We have lightened the bars corresponding to the [-30,-1] bin to better distinguish from the [-60,-31] bin in both Figure 2 and 6.

Figures 3-4: It’s difficult to distinguish cyan arrows over blue background. It’s also difficult to see the wind vectors for the K-transect stations - perhaps these arrows could use heavier line weights and/or different colors?

We have made the suggested figure changes.

Figure 5: Many of the GPH contour labels are cut off at the edges of the figures.

We have made the suggested figure change.

L518: The last four references are not in alphabetic order with the rest of the bibliography.

We have adjusted the placement of references accordingly.

2. Reviewer 2: Charalampos Charalampidis

General comments. The Discussion Paper by Ballinger et al. is an interesting and novel attempt based on in situ, Automatic Weather Station (AWS) observations and Regional-Climate Model (RCM) output to identify the prevailing atmospheric-circulation pattern that causes unseasonal melt events in the southwestern Greenland ice sheet, and whether sea-ice formation and related turbulent-heat production over Baffin Bay in early autumn is of importance.

The study is characterized by an accurate and well-structured methodology, but in my opinion, not also interpretations. As an example, the authors conclude that they “find no evidence to support the hypothesis that local open water and resultant turbulent heating has a demonstrable impact on inland ice melt events”, even though the approach is purely statistical; the study does not disprove the hypothesis, but rather proves that it is not the dominant mechanism.

Structurally, the study suffers from obvious overlooks and requires attention. As examples, I note the allegedly examined AWS pressure and humidity according to the Abstract, even though the analysis is based on AWS air temperature and wind proper- ties only, and the mention of a Sisimiut AWS in the Results and of an Upernavik AWS in the Discussion, without being previously introduced or presenting any related figure in the main body.

I recommend a major-revisions status, primarily to provide the authors with ample time to improve the structure and reasoning throughout the text. I also have a comment on the methodology concerning the AWS analysis that, in my opinion, needs to be addressed before publication.

We appreciate the reviewer’s comments on the paper and have addressed their comments below and in the paper accordingly.

Specific comments

The linguistic level is good, however sentences tend to be condensed, and would benefit by a more elaborate style. Since the study is not purely meteorological and aims potentially to appeal to a wider Earth sciences audience, some effort should be invested into familiarizing readers with meteorological norms instead of just mentioning parameters, numbers, and units. Additionally, the reader’s knowledge over methodological approaches is taken for granted. As a rule of thumb, a second-year Earth- sciences master’s student should be able to follow without referring to textbooks for clarifications.

Revisions are aimed at structural improvements to improve readability in line with the journal’s cryospheric science audience.

The study has a broadly clear structure, but the argumentation is not straightforward, and complicated – sometimes even speculative – discussion points are widespread in Results and Conclusions. Also, as a rule of thumb, referencing supplementary material in Results or other studies in Conclusions should be avoided, in order for the study to be self-standing.

Effort should be invested into describing the theoretical background and the study area, particularly its wind regime and mechanisms, as well as recent Surface Mass-Budget changes within the Introduction or before Data as a self-standing section, so that readers can easily relate afterwards to the Discussion. Recommended literature: Van Angelen et al. (2011), Van As et al. (2014), and the classic GIMEX-90/91 work. The inclusion of a description of the different areas of a glacier, as well as an Equilibrium-Line Altitude definition and how high it is in the study area, is also recommended.

We have touched upon these components through the manuscript where appropriate to complement given research objectives and details of the K-transect study area.

The use of KAN_B observations as basis for the analysis needs to be motivated better than just saying that it records more above-zero Celsius air temperatures than all the other K-Transect AWSs. The way I see it, by the end of August, after the end of the melt season, the increased solar-zenith angle and ice-sheet surface albedo limit the influence of solar radiation on potential ice-sheet surface melt, which is thereafter driven by climatic drivers influencing downward longwave radiation (i.e. cloudiness) and turbulent fluxes (e.g. September 2010; Charalampidis et al., 2015). Also, katabatic-wind flow, driven by the balance of downward sensible heat flux and radiative cooling at the surface, becomes gradually colder and denser, and therefore more intense and laminar, thereby hindering turbulent mixing over large part of the AWS transect that is characterized by decreased surface roughness (Smeets and van den Broeke, 2008; see also specific comments for L208-209 and L211-218). Hence, melt events might occur in cases of weak katabatic-wind flow and concurrent northwesterly atmospheric advection from Baffin Bay, or moderate to strong katabatic-wind flow and concurrent southerly barrier winds along the ice-sheet margin driven by synoptic circulation.

We have clarified our motivation for using KAN_B above (T+) and below (T-) freezing events for compositing across the K-transect, and the compositing methodology, in the Methods section. Acknowledging the ice-albedo feedback is weak in autumn relative to summer months, we have edited the Discussion section to address local, mesoscale, and synoptic winds supporting T+ events. In concluding that synoptic forcing strongly influences our T+ cases, we have also briefly discussed the implications of enhanced moisture advection and resulting cloud longwave effects on melt.

Located only 1 km away from the ice-sheet margin, KAN_B should be the station most sensitive to both these circulation patterns. In both cases, the local boundary layer will become more humid (the role of humidity on energy balance and as a cause of surface melt should be explicitly described), and KAN_B might record positive air temperatures, in which case it is also worth inspecting all on-ice AWSs for positive air temperatures, which would be indicative of surface melt. (It should be explicitly mentioned in the text that positive near-surface air temperature is used as an indicator of melt at the ice-sheet surface.)

A pan-Greenland evaluation of positive on-ice air temperature anomalies (above-freezing or simply above-normal) is beyond the scope of this paper. Future analyses will look to expand the spatial fingerprint of local and remote forcing of marine intrusions on Greenland air temperature

events, but here we wish to focus solely on the data-rich K-transect for this proof of concept assessment.

The statistical analysis should reveal which of the aforementioned cases is the most frequent (and not simply differentiate between regional meteorological processes acting during positive and negative KAN_B air-temperature events, as currently stated in L154-155. What goes on during negative KAN_B – and hence K-transect – air temperatures is not the focus per se; it is just used as means of comparison). The above theoretical introduction material along with Figure 2 alone proves, in my opinion, that synoptic circulation in the South of Greenland is the driver of unseasonal melt events mostly in the lower ablation area until the elevation of KAN_L. The persistent katabatic wind regime acts otherwise as a shield against turbulent forcing from Baffin Bay. All the rest should be an elaboration around this key result.

We have adjusted the wording in the methods section to better focus attention on the common timing and physical processes bringing above-freezing air to KAN_B and S5 and KAN_L, thereby generating “unseasonal” melt at latter those on-ice stations.

It might be insightful to make a similar comparison of KAN_B with observations further away from the ice-sheet margin. I do not know what the result might be, but I am guessing weakening southerly wind away from the margin in case of synoptic-driven, barrier-wind occurrences, and otherwise more intense winds than whatever KAN_B is reporting at that time, directed toward the ice sheet.

As previously mentioned, follow-up analyses will take a wider spatial examination of thermodynamics and dynamics of unseasonal melt.

Nevertheless – and this is my major methodological concern – it is not clear in the text how the KAN_B temperature events are defined. Are these definitions based on hourly or daily observations? Is there a time window plus/minus Δt around a warm/cold KAN_B event t within which the conditions at all other stations are evaluated? Is Δt selected larger or smaller depending on the duration of the KAN_B event t ? Eventually, how sensitive are the statistics, and how conclusive the implications, between hourly and daily analysis? Please, elaborate.

Air temperature composites are based on daily mean air temperature values above and below-freezing at KAN_B. Therefore, T+ is one bin, and T- represents the other bin. We have taken strides to clarify this partitioning in the manuscript. Duration of T+ and T- events and sub-daily analyses are beyond the scope of the study, but will be examined in follow-up research using climatological seasons.

Technical comments

Please, make use of dashes, or hyphens if appropriate, throughout the text to facilitate readability in case of several nouns in a sequence, e.g. in the Abstract alone

We have made recommended changes where appropriate throughout the paper.

*L27: air-temperature episodes; L29: open-water duration; L30: sea-ice advance; L31: sea-ice growth; L38: late-season, ablation-zone melt events, but also L129: “Surface*hyphen*atmosphere features” Also, differentiate between dashes and minuses.*

We have attempted to use hyphens where appropriate and differentiate dashes and minuses in the text.

Use the more appropriate “area” instead of “zone” throughout the text.

We have made the suggested substitutions.

I recommend the use of “observations” instead of “data”, while differentiating between in situ and remotely sensed, and “simulations” for modeling products.

We prefer to use “data” as a more general reference to avoid confusion as the climate science community often tends to characterize reanalysis output, for instance, as observational or modeled based on variable studied.

I recommend the use of “average” instead of “mean.”

We prefer to leave the term “mean” as it is used throughout the paper.

Except for “Buffin DOA”, complete “Buffin” as “Buffin Bay” throughout the text.

We have made the suggested addition of “Baffin Bay” for clarity.

Capitalize the first letters of every word when an abbreviation is introduced, so that the reader’s eye can make a quick connection, i.e. L30: Date Of sea-ice Advance (DOA).

We prefer to leave the referencing as it is given in the manuscript preceding the acronym.

L27: delete “significant”, and reserve it exclusively for describing correlations.

We indicate “significant” as it relates to correlations and t-test differences between T+ and T- events.

L32: “unseasonal melt events. . .”

We are not clear what this comment refers to, but the phrase has been previously defined in the abstract.

L34: “Southwest” or “southwestern”

We have made the suggested change to “southwestern.”

L34: The influence of synoptic and mesoscale systems on the above- and below- freezing near-surface air-temperature events. . .

We have altered the referenced sentence as indicated in the following point.

L35: “AWS” -> “the”; “The in situ observations...”; Why are pressure and humidity observations mentioned here? I was unable to spot them later in the study. Why is wind speed and direction not mentioned?

We have removed the reference to pressure and humidity and inserted some commentary on the AWS wind speed and direction.

L36: “against” -> “with”

We have made the suggested change.

L35-38: I suppose “MAR, RACMO2, and ERA-Interim are used to provide context to the in situ observations by explaining the air-mass origins and the (thermo) dynamic drivers of melt events.” As it is written now, it gives the impression that the in situ observations need to be calibrated against RCMs.

We have altered the wording to clarify the role of MAR, RACMO, and ERA-Interim data. As mentioned, these data provide regional and synoptic context to the local AWS winds. MAR and RACMO have both been extensively calibrated against on-ice AWS observations (e.g. from PROMICE and IMAU station records) as mentioned in the Delhasse et al. (2018) and Noël et al. (2018) references included in the Data section.

L41: Delete “consistent with previous studies”. Try not to refer in the Abstract and Conclusions to other studies.

We have removed this phrase.

L42: Consider removing “pressure-gradient driven” from the Abstract, and describe briefly the mechanism in the Introduction.

We have removed this phrase and paired pressure-gradient discussion with a new composite pressure and 10-m wind figure.

L42: “Katabatic-wind regime”, since the word “katabatic” is an adjective referring to a descending object, in this case, wind.

We prefer to leave as “katabatic regime.”

L41-42: I think this is an overall complicated explanation. I think the primary obstacle of Baffin-Bay marine-air intrusions over the ice sheet should be intuitively the persistent katabatic wind regime that intensifies in the beginning of autumn. Additionally, barrier winds might be present, in which case melt might occur due to air-mass transport from the Atlantic. I propose restructuring as: “. . .are obstructed by the persistent katabatic- wind regime flowing downslope from the ice sheet, and the occasional occurrence of barrier winds along the ice-sheet margin.”, or something along these lines.

We have made a similar change as suggested to clarify the role of katabatic winds in “blocking” the marine layer transport onto the K-transect.

L44: “Substantial mass losses. . .”

We have made the change.

L46: “have become sensitive” or “are becoming increasingly sensitive”

We have made the change to the suggested latter phrase.

L48: Since all Van or Van de Author have been categorized under V in References, consider capitalizing the first letter of “Van” in the in-text occurrences, as well as that of the first author in the References, in order to allow the reader to navigate through easily.

We elect to leave the author’s names as they are given.

L53: Replace “play a key role” by “are of importance”

We have made a similar suggested change.

L54: “surface melt at the southwestern GrIS.”

We elect to more generally include “western” before “GrIS melt.”

L55: “Conflicting evidence have been presented in literature over the past decade regarding. . .”

We have made the suggested change.

L56: “Regional-climate simulations. . .”

We have changed the phrasing to “Regional climate model simulations...”

L60: “noted that. . .”

We have made the suggested change.

L61: Replace “which” by “and”; replace “by” by “to”.

We have made the suggested changes.

L63: “in Ilulissat and Nuuk, approximately 200 [Unit] to the north and south of Kangerlussuaq, respectively. . .”

We have added the appropriate reference to km and “respectively” as suggested.

L66: Replace “coupled” with “correlated”.

We have made the suggested change.

L67: Please, delete “robust”. Statistical quantities are a matter of context, and their interpretation is dependent on the datasets and the research question itself, which in this instance are not present; “(from Markus et al., 2009)”

We have substituted “robust” for “significant” here.

L69: “The authors found that significant, positive correlations between Baffin and Labrador SST and coastal SAT often persist. . .”

We have made the suggested change.

L70: “onset of freeze” should suffice; “Applying a similar correlative approach on. . .”

We have adopted the first change, but elect to maintain rather than change the second wording recommendation for this line.

L71: “while utilizing melt/freeze product. . .”

We have made a slight change in wording here.

L74: “Both studies indicated. . .”; replace “upper-level” with “high-altitude”.

We have made the first change, but elect to keep the second as “upper-level” is commonly used to describe winds in the mid-to-upper troposphere.

L75: Replace “at the limits of” with “toward the end of”.

We have made this change.

L81: Replace “research studies” with “literature”.

We have made this change.

L86: Delete “automatic weather stations”, since AWS has already been introduced.

We have made the change since AWS introduced in the Abstract.

L99: “Daily observations are available over the 1979–2015 period at a . . .”

We have made this change.

L101: Delete “day of sea-ice advance”, since DOA has already been introduced.

We have made this change, but have clarified the DOA metric.

L102: Bliss et al. (in review)

This work is “in press” and we have updated the reference and in-text citation.

L112: “in this study (Fig. 1).”

We have added a the reference to Fig. 1.

L113: “KAN_B that is situated approximately 1 km away from the ice-sheet margin. . .”

We have clarified the statement as suggested.

L117: Delete “tundra (KAN_B only) or glacier ice”

We have made the suggested change.

L116-117: *The observational distance from the surface decreases during winter season due to the accumulating snowcover around the AWSs by as much as two meters depending on the location along the transect, while it increases again each melt season until the complete ablation of the accumulated snowpack. In the case of KAN_U that is located in the lower accumulation area, this distance tends to become shorter over the course of a few positive mass-budget years due to the incomplete ablation of the snow cover, but also due to the sinking of the AWS tripod during ablation in the temperate firn below, as discussed by Charalampidis et al. (2015). After the extreme 2012 melt season, snow accumulated around KAN_U during the 2013 and 2014 positive mass-budget years, while on 3 May 2015 the half-buried tripod was replaced.*

We appreciate the author’s insights on the K-transect AWS air temperature measurement heights, which are complicated by snow accumulation and ablation through the annual cycle. We have added the suggested citation and an acknowledgement that the sensor heights fluctuate with these mass balance components.

L121: Consider including also Citterio et al. (2015) describing the PROMICE AWS.

There are many papers describing aspects of the IMAU and PROMICE AWS networks, but we elect to mention a concise list here.

L125: Delete “have been shown to”

We have made the suggested change.

L127: “from between 1000–200 hPa height, corresponding to the distance between sea level and lower stratosphere at 67 N (e.g. Zängl and Hoinka, 2001). . .”

We appreciate the reviewer’s reference, but we elect to keep the original description of integrated vapor transport (IVT), which is elaborated on in the Methods section and follows from work of Mattingly et al. (20016, 2018).

L129: “Surface*hyphen*atmosphere” since the two are related/interacting.

We have made the suggested change.

L130: Replace “features” with “interactions”. Alternatively, replace “Surface– atmosphere interactions” with “Boundary-layer processes”; 500 hPa height (i.e. ~5000 m above sea level)”

We have replaced “features” with “interactions” as suggested, but elect to maintain variable descriptions.

L132: “10-m above surface and 850 hPa height. . .”

We have shortened the sentence, but elect to keep the core “Wind speed and direction at 10-m and 850 hPa” intact as these represent standard reference levels for these dynamic variables.

L133: “low-level atmospheric flow. . .”

We have made the suggested change.

L143: “ice caps, and improving. . .”

We have made minor edits to the sentence to make it clearer.

L145: “to characterize near-surface. . .”

We have made the suggested change.

L151: It should be mentioned that above 0 C air temperatures at on-ice AWSs are considered an indicator of ice-sheet melt.

We have integrated the suggested addition.

L152-165: It is not clear how the KAN_B temperature events are defined. I refer to Specific comments

We have made efforts to more clearly explain the compositing approach within the Methods section.

L157: “due to the station’s location. . .”

As with the previous comment, we have clarified the compositing approach.

L171: “Based on RCM output, . . .”

We clarify that ERA-Interim data is used for IVT calculation and subsequent classification.

L172: Delete “integrated water-vapor transport”, since IVT has already been introduced.

We have made this suggested change.

L183: Refrain from mentioning supplementary material as part of the text, and only refer to them in parentheses at the end of sentences. Nevertheless, supplementary material should be referenced outside Results, and if Fig. S1 should be referenced in the first sentence of the Results, perhaps it belongs in the main article.

We elect to keep figure references in their current place with the figures included representative of the main results of the manuscript.

L189-191: Nice, but perhaps also mention that the difference has narrowed primarily due to the prolongation of the melt season over the course of the thirty years.

We have added some remarks with regards to melt season lengthening.

L193-195: It is a bit awkward to see all of a sudden a Sisimiut station being mentioned here in the first subsection in Results even though it has not been introduced earlier, and a case being made based on supplementary material. Please, restructure.

We have introduced the DMI surface air temperature data for Sisimiut and Kangerlussuaq AWS at the conclusion of the Data section. We have also clarified their supplemental usage as they relate to the study.

L195-199: This belongs in the Discussion.

We prefer to leave this section in its existing place.

L201: I am not sure I understand what this first sentence is trying to justify. Also, sounds like it belongs in Methods.

This justification refers to K-transect's observationally-rich environment, and the use of AWS networks to resolve the spatial fingerprint of subgrid-scale melt.

L203: Does the term "composite" essentially refer to the average of all instances? Please, clarify.

We have clarified the term in the Methods section.

L206: Second half of the sentence refers to T above 0 C events? Please, clarify.

This refers to differences in T+ and T- events as indicated in the previous sentence.

L208-209: South-southeasterly winds should have a 157.5 degrees direction, given the orientation of the PROMICE AWSs, so what is now written is incorrect. These winds in autumn are katabatic with a downslope direction (90 degrees) deflected 45 degrees to the right by Coriolis force (i.e. southeasterly direction; cf. Van den Broeke et al., 2009), plus potential southerly synoptic influence. Nevertheless, this quantification seems to be more prominent above the long-term ELA and KAN_B. Good thing to also mention.

We have added some text clarifying the wind direction and Coriolis influence citing the van den Broeke paper provided. We have also mentioned statistically significant changes to wind direction above the long-term ELA at S9 and KAN_U within the paragraph.

L211-218: This belongs in the Discussion. Nevertheless, I am not sure I agree with this interpretation, and I explain: Strengthening wind speeds during positive air-temperature events at KAN_B do not reflect strengthening of katabatic flow (i.e. cold, dense wind), but rather that additional wind components inducing turbulent mixing might be present. A strengthened katabatic flow would remain cold, and would be more laminar, and hence less turbulent, than usual. Katabatic wind could enhance turbulent mixing during melt season at the lowermost rough-surface parts of the transect, but we are discussing unseasonal melt events, implying that sunlight is reduced, hence surface melt is not sustained in the way it does during the melt season, while surface roughness below ELA might be substantially decreased due to accumulating snow cover, and above ELA slightly increased for the same reason, i.e. sastrugi formation. The observations from most AWSs within the same averaging periods suggest southerly deviation during positive air-temperature events from the cold-event direction, and the way I perceive it, southerly synoptic influence. I note that Figure 2 and Table 2 suggest that melt might occur primarily at the two lowermost on-ice AWSs, while wind speed as well as wind-speed differences between positive and negative cases within the same averaging periods are more pronounced at higher elevations due to comparatively reduced surface roughness (cf. Van den Broeke et al., 2009).

We have revised our wording here and softened the language. We appreciate the reviewer's feedback and elect to include the present list of factors. As we suggest, these may contribute to

the wind speed intensification and therefore link with turbulent flux analysis that is subsequently presented in the paragraph.

L214-215: Positive energy flux that contributes to ice melt is most definitely downward, i.e. directed from the atmosphere toward the ice-sheet surface, and not necessarily the result of increased wind, rather the result of increased turbulence; “Sensible heat fluxes” does not sound nice. Consider removing the plural.

We have made the suggested changes, acknowledging the heat flux sign was incorrectly described.

L219: The first sentence is not a result. Please, delete or relocate to Introduction.

We have added “The K-transect” at the sentence outset to provide context to the result.

L222: “at KAN_M and S9 in the upper ablation area.”

We have made the suggested change.

L223: Replace “modeled” with “simulated”.

We have made the suggested change.

L223-225: Difficult sentence, consider revising. Also, please, relocate in the Discussion.

We have elected to remove part of the sentence that is largely duplicative with text earlier in the section.

L228-229: This sentence, as it is, belongs in the Discussion. You can reformulate and keep in the Results as: “We note that there is a height difference between the RCM 10-m above-surface output and the measuring heights of the AWSs, as mentioned in the Data section.”, or something like this.

We have altered the sentence and elect to keep it in its present place.

L233-234: This first sentence is Discussion material. Please, relocate or reformulate, since it sounds like a rather abstract introductory sentence referring to the previously outlined results.

We have integrated this sentence into the Discussion content.

L239: Explain the significance of 540 dam (i.e. 5400 geopotential meter), i.e. it often distinguishes solid and liquid precipitation.

We have added details as requested on the 540 dam contour and included its label in Fig 5 panel plots.

L255: *The link between moist air masses and how they may facilitate ablation-area melt is not clear. Please, elaborate preferably in the Introduction.*

We have added “warm” as is evident when they pass over the GrIS by the increasing height values, tropospheric moisture content, and K-transect surface air temperatures.

L261: *Include a short comment on strong negative NAO phases, as seen in monthly observations.*

We have added the suggested change.

L266: *“turbulent atmospheric heating”*

We have made the suggested change.

L267-269: *Please, refrain from referring to supplementary material as main part of the text, i.e. delete “As shown in Fig.S6”. Instead, include a citation at the end of the sentence. It should be mentioned that it is a moderate to weak link that seems to be year-dependent. The way I perceive it, this differentiation amongst years suggests synoptic-circulation control that may or may not be present each year, and that is a good comment to include before anything else. (For example, Fig. S6 suggests weak correlation in autumn 2013 between local sea-surface temperature and AWSs, when limited melt occurred even at KAN_U (September 2013; Charalampidis et al., 2015).*

We adjust the reference to the end of the sentence and restructured the wording. Last in the paragraph we posit that the synoptic control may be stronger in years of higher correlation, and a deeper examination is currently being conducted in related work.

L275: *“statistically robust co-variability”*: Please, remove “robust” and reformulate.

We have changed “robust” to “significant” to be consistent with other correlative findings.

L271-279: *This part seems somewhat arbitrary, since no evidence of a different wind regime between 2011–2012 and 2013–2015 was presented. Also, I am not sure I agree with the categorization. Please, revise/clarify.*

We are suggesting some physical linkages, supported by literature, that could explain strong versus weak interannual correlations along an “extended transect” at 67°N between near-shore SSTs and coastal and on-ice air temperatures. In doing, we address some reasons why the coastal response to sea-ice heat flux feedbacks might be strong, yet very localized. We expand on these concepts further in the following paragraphs of the discussion.

L287: *Mention also the distance from Kangerlussuaq.*

We have added this information.

L290-294: This is highly unclear and speculative. Please, revise.

We have revised this area by highlighting that increased ice sheet radiational cooling over the ice sheet interior versus coast, which helps to propagate katabatic winds that block inland penetration of marine air.

L295: “appears to be of minor importance. . .”

We have made a minor wording change.

L304-306: Please, clarify.

We have clarified the language in the sentence.

L306: “Denmark Strait and Irminger Sea at the East coast of Greenland. . .”

We have made a similar change to clarify Denmark Strait and Irminger Sea location with respect to Greenland.

L316: Generally, Conclusions outline key findings in the Results and key Discussion points. The current state appears more like just another part of the Discussion, while the only Concluding bits are between L319-324 and L341-345. Please, consider rewriting the whole section outlining important quantifications from Results. Please remove all citations, as the Conclusions should refer only to the present study, and should be self-standing.

We have removed some of the redundant citations, but have kept those in reference to future research avenues that dovetail from our main results. To that point, we have made an effort to further emphasize the main manuscript results in the Conclusions section.

L317-319: Consider simplifying; rephrase “around the limits”

We have changed wording to clarify the limits previously mentioned.

L377: Delete “2018”

We have updated the reference.

*Table 1: Include a minus in front of the 1 km of KAN_B, so the reader can immediately see that it is different from the rest of the stations. “50*hyphen*150 m”*

We have described KAN_B’s position in the caption.

Table 2: Were these daily averages? Please, clarify. Note that dashes have been used instead of minuses. Also, make column lines between columns 3-4 and 5-6 thicker to facilitate the eye of the reader.

We have clarified that the counts involve daily mean air temperatures. We have also thickened the line between the columns as suggested.

L540: Replace “30 to 60-day window” with “time window defined by the 60th and 30th day before day of ice advance (DOA)”

We have clarified the caption.

Figure 2: Include the legend that is shown in panel a also in b and c. In panel c, include also N-S-E-W. In panel d, are these points in reference to daily or hourly values? Please, specify.

We have included legends for panels b and c, and added North, East, South, and West accordingly to panel c. We have also clarified the “daily mean” values in panel d.

L551: Define “composites” better.

As the composite methodology has been clarified in the Methodology section, we wish to keep the captions concise.

L552-553: Difficult to fathom. Please, clarify.

We have clarified the caption.

L553: “selected”

We wish to keep the wording the same.

L569: Spell out IVT and include abbreviation since it is used as such in the figure.

We have made the suggested change.

Figure 6: Include legend in both panels. In the caption, spell out all abbreviations and include abbreviation in parentheses.

We have included the legends in both panels and have spelled out abbreviations not previously listed in captions.

L754: Define “composites” better.

As the composite methodology has been clarified in the Methodology section, we wish to keep the captions concise.

L577-578: Difficult to fathom. Please, clarify.

We have clarified the caption in a similar manner to the Figure 2 caption (L552-553).

Table S1: Dashes as minuses. Please, correct. "2011*hyphen*2015"

We have made the suggested change.

Figure S2, S3, S4, S5: Spell out DOA initially, and then use abbreviation.

We have spelled out date of sea ice advance (DOA) in all captions after the terms initially appear.

Figure S4, S5: Define composites better.

As the composite methodology has been clarified in the Methodology section, we wish to keep the captions concise.

Figure S6: Introduce SST properly in caption.

We have spelled out SST as suggested.

References

Charalampidis, C., van As, D., Box, J. E., van den Broeke, M. R., Colgan, W. T., Doyle, S. H., Hubbard, A. L., MacFerrin, M., Machguth, H., and Smeets, C. J. P. P.: Changing surface-atmosphere energy exchange and refreezing capacity of the lower accumulation area, West Greenland, *The Cryosphere*, 9, 2163-2181, doi:10.5194/tc-9-2163-2015, 2015.

Citterio, M., van As, D., Ahlstrøm, A. P., Andersen, M. L., Andersen, S. B., Box, J. E., Charalampidis, C., Colgan, W. T., Fausto, R. S., Nielsen, S., and Veichert, M.: Automatic weather stations for basic and applied glaciological research, *Geol. Surv. Denmark Greenland Bull.*, 33, 69–72, 2015.

Van Angelen, J. H., van den Broeke, M. R., and van de Berg, W. J.: Momentum budget of the atmospheric boundary layer over the Greenland ice sheet and its surrounding seas, *J. Geophys. Res.- Atmos.*, 116, D10101, doi:10.1029/2010JD015485, 2011.

Van As, D., Fausto, R. S., Steffen, K., and the PROMICE project team: Katabatic winds and piteraq storms: observations from the Greenland ice sheet, *Geol. Surv. Denmark Greenland Bull.*, 31, 83–86, 2014.

Zängl, G., and Hoinka, K. P.: The Tropopause in the Polar Regions, *J. Climate*, 14, 3117–3139, doi: 10.1175/1520-0442(2001)014<3117:TTITPR>2.0.CO;2, 2001.

3. Anonymous Reviewer #3

General comments:

Ballinger, et al propose a hypothesis for the onset of late-season melt events on the Western Greenland ice sheet. Some prior literature has suggested that open-water ice-free conditions in Baffin Bay cause melt incursions onto the ice sheet, but Ballinger, et al use weather stations data, regional climate models and reanalysis products to make a case that incursions of North Atlantic warm air are responsible for these late-season events, regardless of sea-ice conditions.

*Overall, the hypothesis is novel, and I applaud the authors for bringing in multiple datasets to support it. As one of the other reviewers also noted, I am, however, very concerned that the short time series (2011-2015) limits the conclusions that can be made with any statistical certainty. From the evidence given, I would say the study is suggestive, but not conclusive in its arguments. In my opinion, the authors have a choice: either use a longer time-series of measurements or model data (for instance, keep the 2011-15 analysis of AWS data but make the regional climate data analysis span from 1979-2015, which is possible given that the two datasets aren't even used in direct comparison to each other), *or* soften the conclusions to make it clear they are suggestive but not entirely conclusive given the short time series. With only 5 years at your disposal, random noise can easily be interpreted as interesting new patterns.*

As always, I acknowledge that the authors have spent more time considering this paper than reviewers spend reading it. If authors believe my judgements are unfounded or based on a misunderstanding, or if I just missed something in a comment, they may of course make that case upon resubmission to the reviewers or editor. Overall I do think the study, and the hypothesis put forward, is quite suggestive and worth publishing for that reason, even with the concerns cited, but the concerns should be addressed.

We thank the reviewer for constructive comments and have addressed their concerns in an attempt to improve the quality of the manuscript.

Specific comments:

*L31-32: "For the unseasonal melt period preceding the DOA" . . . this make it sounds as if it's referring to a *specific* melt event that hasn't yet been mentioned. Generalizing the sentence more to something like "For periods of unseasonal melt preceding the DOA, . . ." may be clearer to the reader.*

We have clarified the wording as suggested.

L34-35: "the above and below freezing surface air temperature events. . ." same comment as above.

We have made a similar suggested change.

L83-84: “temporally-anomalous GrIS late melt events” : in much of the text, terms such as “unseasonal” and “temporally-anomalous” are used, but never really defined. Does is refer to melt events after a certain date/season? Recent late-season melt events that are more frequent than previous periods? The descriptor is a bit vague here.

We have clarified the language, relating late-season melt (as in the manuscript title) to “unseasonal” so as show the reader the terms are used interchangeably.

L104: (quick format check) Several headings are not “bolded”, while the rest are. Quick fixes.

We have made bolded headings for consistency.

L119: “erroneously low values are filtered out prior to analyses” : Which variables were filtered in this way: temperature, wind speed, others? If you can, be more specific.

We have clarified the which variables were filtered.

L152: “A composite approach is applied to characterize atmospheric conditions. . .” : From what I saw, I couldn’t find an explanation in the text of how these composites were put together, or what exactly the reader is looking at when seeing the composite numbers in the tables and figures. I don’t expect the authors to provide a textbook lesson on composite statistics, but a brief 1-3 sentence explainer for the reader would help reproducibility and clarity of the text. Right now, if I took the same data and tried to reproduce the results I would have no guidance of how to perform the composite analysis other than the authors’ word that they applied a “composite analysis.” More specificity is needed here to make the results reproducible. If the method is identical to one used in other papers, a citation may suffice.

We have clarified the composite approach in the Methodology section so that results could be reproduced for additional transects about the GrIS, for instance.

L162-165: The description of the timespans used in the composite approach is good, I would put this at the top of the paragraph before describing why composite approaches were used and what constraints were placed upon them.

We have re-arranged the composite descriptions to introduce the temporal restraints before discussing the temperature bins. Care has also been taken to clarify the methodology as mentioned in the previous comment and following the recommendations of the other reviewers.

L183: “Perspectives on... are shown” is a vague term, almost meaningless. If the sentence is meant to point out something specific that Figure S1 shows, describe it explicitly.

We have edited the wording to be more direct in what Fig. S1 is presenting.

L183-199: The first several paragraphs of the Results refer to figures that are almost exclusively in the supplement (Figs S1-S3, with exception of the Fig. 1 map), which makes it awkward for the reader to follow along. These figures appear to be central to the results, not just supplementary. Unless you are limited by the number of figures, consider putting some of these in the central text rather than forcing the reader to flip back and forth to an entirely separate document just to follow along with your argument.

We prefer to include figures corresponding to the main manuscript results (i.e. local and regional drivers of K-transect melt events) as they are currently placed, and leave the introductory results on GrIS and Baffin Bay end of melt season overviews, for example, as Supplementary Material.

L192-193: “Relative to the climatology. . . date in 2012-2015 (Table S1).” It is unclear why 2011 is separated from 2012-2015 here, or why this sentence exists at all. Inter-annual variability has always been present, and no evidence is provided that this juxtaposition of years shows any more significant differences than any other random 5-year period in Greenland’s climatological history (perhaps it is, but it isn’t demonstrated). If not, just omit it.

As shown in Table S1, the date of Baffin sea ice advance (DOA) in 2011 was the only year of the five years studied with anomalously early ice formation. We wish to briefly note this anomaly as we describe the late melt season characteristics setting the stage for the core results of the paper.

L195-199: “Interannual differences. . . found in the east and north (Curry et al., 2014).” These sentences don’t show new results, but discuss the context of other literature. Consider moving to Discussion.

We elect to keep these results in their original place to provide context on the ice melt season preceding the primary results of the paper.

L201-202: “The spatial coherence of observations across the K-transect along with inhomogeneous GrIS Region 3 spatial melt patterns and satellite pixel contamination issues at the tundra-ice interface, lead us to assess the melt events at the station level.” It’s very unclear what is meant by “inhomogeneous GrIS Region 3 spatial melt patterns”, or why that would motivate a K-transect station-level approach. Please clarify. Similarly with “the spatial coherence of observations across the K-transect”.

In the vast GrIS region (~539,375 km²) melt is not spatially, nor temporally, consistent. For instance, on the same early autumn day the southern region may experience a strong warming signal, but the northern-most bounded area may not. Due to this inconsistency and issues classify melt for pixels intersecting the land surface, we focus on a station-based approach to identifying on-ice melt events. We have further clarified the language in results section 4.2 to further reflect our justification as mentioned.

L208-209: “. . . and comparatively becomes slightly more southerly” One issue with the way these composite records are presented is that there are no uncertainties or spreads presented with them at all, other than which ones are/aren’t statistically significant. Thus, comparisons between them, such as “slightly more southerly” are impossible to make without knowing whether or not the difference are simply within the noise of the two datasets, or are just part of statistical noise. This is the case with all the comparisons, actually, and it makes the conclusions difficult to defend.

We acknowledge that there are some shortcomings of the composite methodology as mentioned in your comment, and our comparisons (by time window and temperature threshold) are the main comparisons we explore through the paper.

L223: “Modeled wind speeds are more intense during T+ versus T- events” How much more intense? 2 %? 150 %? As noted in the comment above, is the difference greater than statistical noise?

We have noted that simulated winds during T+ versus T- events are ~20-50% stronger consistent with the differences in the AWS observations.

L227: “with low root mean squared errors (not shown).” Unless I’m misunderstanding this statement, RSMEs for two values should just be two numbers. They can be stated explicitly instead of just saying (not shown). If they weren’t computed, this statement should be omitted.

We have summarized the RMSE for the model and observational comparisons mentioned.

L227: A slight positive bias in both models is evident. . .” I assume a slight positive bias in wind speed? Clarify so that the sentence can stand on its own without ambiguity.

We have clarified the wording here.

L235: The “North Atlantic region” is not explicitly defined here, it is just vaguely referenced even though the authors are clearly looking at particular portions of the map. This ambiguity makes the rest of the entire paragraph extremely difficult to decipher from a reader’s perspective, given that different portions of “the North Atlantic” behave in different manners in Figure 5.

We have clarified our reference area by mentioning Greenland as the geographic focus within the Northwest Atlantic region.

L235-238: “Whereas T- events “left panels” tend to be characterized by northerly winds over the 1000-700 hPa layer, . . .” It is extremely unclear what is being referred to here. Are these northerly winds specifically in Baffin Bay, or over the whole figure, or. . . ?? Also, this sentence is disjointed and somewhat convoluted, its meaning unclear to the reader.

The “panels” refer to Figure 5 and to clarify we direct the reader back to these in the text.

L238: "found over ice sheet" -> "found over the ice sheet"

We have made the suggested change.

L238-239: "with the 540 dam contour" The 540 dam contour is very unclear in most panels of figure 5. Consider making it clear to the reader exactly which contour is 540 without them needing to interpolate between other lines, if you're going to make a point specifically about the 540 line. Make it easy on your readers to see your point. (Also, as another reviewer noted, make contour labels fully visible, not partially cropped by the panel edge.)

We have made all contour lines visible and labeled the 540 line so that it is easier for the reader to compare its position between T+ and T- events.

L246-255: I found this paragraph particularly good and compelling.

Thank you for your comment.

L265: "toward earlier (later) melt (freeze)" I understand this sentence construct, and occasionally it's useful, but it's also extremely awkward to read and should only be used when necessary to save space. In this case, "toward earlier melt and later freeze" says the same thing with only one more word, and is much clearer English for the reader to understand.

We have made the suggested wording change.

L265: "This hotspot of melt" It's unclear if you're referring to a particular hotspot of melt referred to earlier (if so, point it out), or making a more general statement here.

We have generalized the wording as suggested.

L267-269: "Sisimiut SSTs fluctuate. . . ablation zone at S9." It's unclear why this sentence is important. Additionally, it's unclear that a statistically significant difference can be inferred at all if it only happened in 3 of 5 years, but not the other two. Even with just 5 years of data it's hard to make firm conclusions about climate patterns. . . moreso if just picking three years selectively out of those five. This needs to be better justified, or omitted completely.

This sentence references correlations between local SSTs and air temperatures extending from the coastal to lower accumulation zone at KAN_U. S9 marks the location from which the correlations in most years drop off and are generally weaker toward the interior. We have clarified the wording in the paragraph to reflect this statistical finding.

L271-279: The two points made at the end of this paragraph seem difficult to support conclusively with only 5 years at your disposal, comparing the first two years to the second three. The problem with such a short time series is that signals can be easily interpreted from random noise, making such conclusions problematic at best. This is emblematic of the greatest weakness of the whole paper, making strong conclusions about climate patterns from only five years of data. It is unclear that if you had a 30- year record (long enough to infer at least some of the variability of the patterns you describe), that the same inferences could be made in any significant way.

We acknowledge that five years of K-transect case studies provide a limited temporal perspective and therefore must be considered in light of the evidence presented that Baffin open water and onshore winds do not appear to be a primary factor driving late-season melt events. However, the study provides a framework to be expanded upon in future, related studies presuming the on-ice AWS programs continue for years to come.

L289: “near-surface air penetrates at least to” -> “near-surface air often penetrates at least to” (There isn’t any indication that it always does.)

We have made the suggested change.

L300-301: “positive (negative) GBI (NAO) values” -> “positive GBI and negative NAO values” (more readable)

We have made the suggested change.

L332-334: It is good that the authors recognize that a longer time series would help with these analyses. It is still unclear that all of the conclusions in the paper can be made so confidently with the short time series available, and that some of the results are more just “suggestive” than “conclusive.”

As mentioned above, we acknowledge that five years of analysis precludes overconfidence in the results. However, the study provides a framework to further explore unseasonal GrIS melt characteristics amidst ongoing expansion of the Arctic melt season.

Greenland Ice Sheet late-season melt: Investigating multi-scale drivers of K-transect events

Thomas J. Ballinger¹, Thomas L. Mote², Kyle Mattingly², Angela C. Bliss³, Edward Hanna⁴, Dirk van As⁵, Melissa Prieto¹, Saeideh Ghahreghahi¹, Xavier Fettweis⁶, Brice Noël⁷, Paul C.J.P. Smeets⁷, Carleen H. Reijmer⁷, Mads H. Ribergaard⁸, and John Cappelen⁸

Correspondence to: Thomas J. Ballinger (tballinger@txstate.edu)

¹Department of Geography, Texas State University, San Marcos, TX, USA

²Department of Geography, University of Georgia, Athens, GA, USA

³College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA

⁴School of Geography and Lincoln Centre for Water and Planetary Health, University of Lincoln, Lincoln, UK

⁵Geological Survey of Denmark and Greenland, Copenhagen, Denmark

⁶Laboratory of Climatology, Department of Geography, University of Liège, Liège, Belgium

⁷Institute for Marine and Atmospheric Research, Utrecht University, Utrecht, the Netherlands

⁸Danish Meteorological Institute, Copenhagen, Denmark

Manuscript submitted to *The Cryosphere Discussions* on 19 December 2018, revised on 10 April 2019

Abstract. One consequence of recent Arctic warming is an increased occurrence and longer seasonality of above-freezing air temperature episodes. There is significant disagreement in the literature concerning potential physical connectivity between high-latitude open water duration proximate to the Greenland Ice Sheet (GrIS) and late-season (i.e. end-of-summer and autumn) GrIS melt events. Here, a new date of sea ice advance (DOA) product is used to determine the occurrence of Baffin Bay sea ice growth along Greenland's west coast for the 2011–2015 period. Over the two month period preceding the DOA, northwest Atlantic Ocean and atmospheric conditions are analyzed and linked to late-season melt events observed at a series of on-ice automatic weather stations (AWS) along the K-transect in southwestern Greenland. AWS wind speed and direction characteristics are evaluated for above and below-freezing surface air temperature events before the DOA occurs. Surrounding ice sheet, tundra, and coastal winds from Modèle Atmosphérique Régional (MAR) and Regional Atmospheric Climate Model (RACMO) provide high-resolution spatial context to AWS findings, and are analyzed along with ERA-Interim reanalysis fields to understand the meso-to-synoptic scale (thermo)dynamic drivers of the melt events. Results suggest that late-season melt events occurring in the ablation area of the K-transect are strongly affected by ridging atmospheric circulation patterns that transport warm, moist air from the sub-polar North Atlantic toward west Greenland. While thermal conduction and advection off south Baffin Bay open waters impact coastal air temperatures, local marine air incursions are obstructed by barrier flows and persistent katabatic winds along the western GrIS margin.

Deleted: unseasonal

Deleted: late

Deleted: For

Deleted: unseasonal melt

Deleted: unseasonal

Deleted: Mesoscale and synoptic influences on t

Deleted: he

Deleted:

Deleted:

Deleted: are assessed through analyses of AWS wind, pressure, and humidity observations

Deleted: These surface observations are further compared against

Deleted: ,

Deleted: 2

Deleted: airmass origins and

Deleted: the K-transect

Deleted:

Deleted: ,

Deleted: ablation zone

Deleted: consistent with previous studies,

Deleted: from Baffin Bay onto the ice sheet

Deleted: the

Deleted: pressure gradient-driven

Deleted: regime

5 **1 Introduction**

Substantial decline in Arctic sea ice extent and mass loss from the Greenland Ice Sheet (GrIS) have been observed for the last four decades (e.g. Serreze and Stroeve, 2015; Bamber et al., 2018). Under sustained climate warming, sea and land ice are becoming increasingly sensitive to changes in the frequency and duration of anomalous weather patterns (e.g. Overland and Wang, 2016; Hanna et al. 2014, 2018b). The overall mass balance of the GrIS has contributed roughly 0.5 mm year⁻¹ to global mean sea level rise since the early 1990s (van den Broeke et al., 2016), with about 60% of the mass loss attributed to a decline in surface mass balance (SMB) and 40% associated with increased ice discharge (van den Broeke et al., 2017). Observed warming of near-surface ocean waters west of Greenland since at least the early 1990s is linked to accelerated submarine melt and outlet glacier retreat (Holland et al., 2008; Straneo and Heimbach, 2013) concurrent with more frequent summertime air temperature extremes along the coast (Hanna et al., 2012, Mernild et al., 2014). These findings raise the question of whether Baffin local ocean conditions are of importance in governing the spatial extent and temporal variations in western GrIS melt.

Conflicting evidence has been presented in literature over the past decade regarding the importance of the warming of the nearby ocean on GrIS surface melt. Regional climate model simulations have suggested that local sea surface temperature (SST) impacts on GrIS climate and SMB are negligible due to offshore flow arising from a prevailing katabatic wind regime (Hanna et al., 2014; Noël et al., 2014). Using a statistical approach, Rennermalm et al. (2009) found contemporaneous Baffin open water (<15% sea ice concentration (SIC)) and western GrIS melt to be positively correlated in late summer (1979–2007). The authors noted that the strongest, statistically significant correlation (r=0.71) was observed in August near the K-transect (Fig. 1), and was attributed, in part, to wind-driven onshore transport of warm marine air. Hanna et al. (2009) evaluated lagged correlations between July coastal air temperatures at Ilulissat and Nuuk (~200 km north and ~300 km south of Kangerlussuaq, respectively) from Danish Meteorological Institute (DMI) weather stations and adjacent, offshore HadISST1 SST values in the preceding and following 2 months. The authors noted a simultaneous, positive SST relationship with Ilulissat temperatures (r=0.56), while Nuuk temperatures were significantly correlated with offshore May–July SSTs (r>0.50) over the 1977–2006 record. Ballinger et al. (2018a) found significant interannual correlations (r>0.40, p<0.05) during 1979–2014 between Baffin freeze onset dates (from the Markus et al., 2009 product) and September–December surface air temperatures (SAT) at most DMI stations found along the west Greenland coastline. The authors found that significant, positive correlations between Baffin and Labrador SST and coastal SAT often persist through December after the onset of freeze. Applying a similar approach and melt/freeze dataset, Stroeve et al. (2017) showed Baffin and GrIS melt and freeze behaviors to be synchronous. The authors noted that years with anomalously early sea ice melt tended to have strong, upward turbulent heat fluxes and westerly winds atop developing open water that transported surplus heat and moisture onto the ice sheet. Both studies indicated that the synoptic, upper-level circulation pattern is critical for modulating poleward heat and moisture transport and the surface warming/melt processes toward the end of the melt season. Ballinger et al. (2018a) proposed a sea ice-heat flux feedback whereby upward turbulent heat fluxes from Baffin Bay help maintain the high-pressure block aloft, with anticyclonic southerly winds both inhibiting the autumn/winter ice pack formation and transporting warm marine air onto the western Greenland coast. This potential

- Deleted: ignificant
- Deleted: mass losses
- Deleted: and
- Deleted: have
- Deleted: e
- Deleted: Greenland Ice Sheet (
- Deleted:)
- Deleted: surface mass balance (SMB) decrease
- Deleted: waters
- Deleted: a rise in
- Deleted: warm
- Deleted: play a key role
- Deleted: Scholarship published during the past decade has presented conflicting evidence
- Deleted: ing experiments
- Deleted: which
- Deleted: by
- Deleted: upled
- Deleted: robust
- Deleted: correlations
- Deleted: commencement
- Deleted: onset
- Deleted: correlative
- Deleted: product
- Deleted: at
- Deleted: limits

mechanism may have contributed to record Greenland Blocking events that occurred in October over successive years during the early-to mid-2000s (Hanna et al., 2018a).

A paucity of literature, focused on the Baffin Bay open water influence on GrIS melt and SMB has left open the question of potential physical linkages. Our primary goal in this paper is to evaluate and determine whether the local ocean-atmosphere interactions have played a role in late-season GrIS melt events spanning the end of boreal summer through autumn, (e.g. Doyle et al., 2015; Stroeve et al., 2017). We posit that if Baffin Bay open water were to influence GrIS late-season melt events, the heat accumulated in the marine layer from ocean-to-atmosphere turbulent fluxes, would be transferred directly to the ice sheet by onshore westerly winds. In addressing this hypothesis, our analyses are geographically focused on the western slope of the GrIS with emphasis on the K-transect (Fig. 1) as this area – with its two on-ice AWS networks (described in Section 2.1) – is rich with in situ records relative to the remainder of the ice sheet. We analyze meteorological data from these in situ sources and additionally from regional climate models and global meteorological re-analyses to address potential links between GrIS late season melt and the local-scale Baffin Bay marine layer for the period of overlapping data, 2011–2015. For completeness, we subsequently expand the scale of meteorological analyses to consider the influence of greater northwest Atlantic synoptic patterns on the melt episodes. The paper is organized as follows: Section 2 outlines data sources, Section 3 describes methods employed, Section 4 covers the local and synoptic scale atmospheric interactions with GrIS melt, Section 5 discusses key results, and Section 6 offers concluding remarks and makes suggestions for future research.

2 Data

2.1 Passive microwave records

Sea ice data are from the National Oceanic and Atmospheric Administration/National Snow and Ice Data Center (NSIDC) Climate Data Record of Passive Microwave SIC v3r1 product distributed by NSIDC (Meier et al., 2017). We use the “Goddard Merged” SICs that are produced using a combination of the NASA Team and Bootstrap algorithms applied to satellite passive microwave brightness temperatures (Peng et al., 2013). Daily observations are available over the 1979–2015 period at a 25 km by 25 km nominal grid spacing. The time series of daily SIC at each grid cell were used to identify the sea ice date of advance (DOA), which is the date when SIC increases to 15% for the first time following the sea ice extent (SIE) minima after Steele et al. (2019). Regional mean DOAs for Baffin Bay were obtained from Bliss et al. (2019). The local DOA was determined from the time series of SICs between 1 October and 31 March at each grid cell, then the local mean DOA was computed from 13 grid cells within the domain 66.5 to 67.5°N and 53 to 55°W. SIE was computed by summing the area of grid cells (in km²) where SIC ≥ 15%. At the same spatial resolution as the SIC product, the passive microwave daily GrIS melt time series of Mote (2007, 2014) is also used to classify the ice surface environment in a binary manner (i.e. melt/no melt). Following the Ohmura and Reeh (1991) topographic regions, we assess GrIS melt conditions on the west-central portion of the ice sheet bounding the K-transect.

2.2 AWS data

Meteorological conditions from two AWS networks, the Programme for Monitoring of the Greenland Ice Sheet (PROMICE; stations prefix “KAN”) and Utrecht University Institute for Marine and Atmospheric Research (hereafter IMAU; stations prefix “S”), are used in this study (Fig. 1). In order to include the westernmost PROMICE

Deleted: in October

Deleted: research studies

Deleted: recent,

Deleted: temporally-anomalous

Deleted: late

Deleted: the end of

Deleted: o

Deleted: freeze-up of adjacent ocean waters

Deleted: Ice sheet

Deleted: automatic weather station (

Deleted:)

Deleted: T

Deleted: data are available daily,

Deleted: ,

Deleted: date of sea ice advance (

Deleted:)

Deleted: Peng

Deleted: 8

Deleted: 8, in review

Formatted: Font: Bold

Deleted: K-transect station

Formatted: Font: Bold

Formatted: Font: Bold

station KAN_B that is situated approximately 1 km away from the ice-sheet margin, analyses begin in 2011 and
125 conclude with the end of the DOA record in 2015. Data are obtained and analyzed from seven weather stations
distributed across the K-transect at ~67°N during this period. The transect spans an area from low-elevation tundra,
approximately 1 km inland from the ice sheet glacier terminus (KAN_B), to the lower accumulation area (~1800 m)
at >140 km from Russell Glacier terminus (KAN_U; see **Fig. 1 & Table 1**). AWS data used here are recorded at a
130 height of approximately at 2–3 m above the surface, though observed values fluctuate due to snow accumulation and
melt season ablation (Charalampidis et al., 2015). Daily mean air temperature (°C), wind speed (ms⁻¹), and wind
direction (0–360°) are obtained from IMAU and PROMICE station networks. Most data series are complete for the
study period, but missing or erroneously low values in the temperature and wind variables are filtered out prior to
analyses. Additional details on the respective PROMICE and IMAU AWS programs can be found in van As et al.
(2011) and Smeets et al. (2018). We supplement K-transect data with daily mean DMI AWS surface air temperatures
135 obtained from Sisimiut (WMO code 4234) and Kangerlussuaq (WMO code 4321). These data are used to further
evaluate spatial links between local Baffin Bay open water and air temperatures from the tundra regions below the K-
transect (Cappelen, 2018, 2019; Fig. 1).

2.3 Atmospheric reanalysis and regional climate model fields

A number of ERA-Interim reanalysis (Dee et al., 2011) variables are selected for the analysis of atmospheric
140 conditions across Greenland and the northwestern Atlantic Arctic sector. ERA-Interim surface and upper-air
temperatures, wind speeds, and moisture conditions exhibit relatively small biases compared to Arctic observations
(Bromwich et al., 2016). Regional climate models MAR and RACMO2 are also forced with ERA-Interim fields at
their lateral boundaries. Tropospheric winds and specific humidity from 1000-200 hPa are used to calculate a moisture
flux variable referred to as integrated water vapor transport (IVT); IVT is then classified using a self-organizing map
145 (SOM) approach (see formal description in the Methods section below). Surface-atmosphere interactions and regional
circulation are further evaluated with ERA-Interim latent and sensible heat flux data, 500 hPa geopotential heights
(GPH), and 1000-700 hPa mean winds at the native 80 km resolution.

Wind speed and direction at 10-m and 850 hPa from MAR and RACMO2 are evaluated to understand low-
150 level atmospheric flow over ocean-land-ice sheet areas surrounding the K-transect. Secondly, we briefly discuss
inter-model differences within the planetary boundary layer and biases against AWS observations. Both regional
climate models are specifically developed for simulating polar weather and climate, in particular over the Greenland
ice sheet (e.g., Fettweis et al., 2011; Noël et al., 2018). MAR v3.9 fields at 15 km are used here (see Fettweis et al.
2017 for a detailed model description). Relative to MAR v3.8 used in Delhasse et al. (2018), the main changes to
155 MAR v3.9 consist of enhanced computational efficiency, adjustments to some of the snow model parameters to better
compare with in situ observations, and improved MAR dynamical stability by increasing the atmospheric filtering.
RACMO2.3p2 fields at a horizontal resolution of 5.5 km are also used (Noël et al., 2018). Model physics have not
changed relative to the previous 11 km version described in Noël et al. (2018). The refined spatial resolution of the
host model improves the depiction of topographically complex terrain at the GrIS margins, such as small peripheral
glaciers and ice caps, and the representation of near-surface, local winds.

2.4 North Atlantic atmospheric indices

Deleted: zone

Deleted: tundra (KAN_B only) or glacial ice

Deleted:

Deleted: have been shown to

Deleted: , summarized in this section,

Deleted: known

Deleted: features

Deleted: using

Deleted: Model output u, v, w

Deleted: improving

Formatted: Font: Bold

Daily atmospheric indices are examined to characterize near-surface and upper-level conditions within a historical context. The Greenland Blocking Index (GBI) (Hanna et al., 2018) describes daily mean 500 hPa geopotential height values from 60-80°N and 20-80°W. The North Atlantic Oscillation (NAO) index used here is adapted from Cropper et al. (2015) and represents station-based daily mean sea-level pressure differences between Iceland and the Azores. Both versions of the respective indices are normalized by their day of year means and standard deviations for the common 1951–2000 base period.

3 Methods

Above-freezing air temperatures at on-ice AWS locations represent an indicator of ice-sheet melt. A composite approach is applied to characterize atmospheric conditions underlying late-season GrIS melt events, defined here as occurring at the conclusion of boreal summer (i.e. late August) and during autumn preceding sea ice advance on Baffin Bay (**Table S1**). Two constraints are placed on the composite analyses. The first constraint involves the length of the analysis period prior to DOA. Through lead/lag correlations of recent data series of ≥30 years, Hanna et al. (2009) and Ballinger et al. (2018a) noted Baffin Bay ice coverage and sea surface temperatures in the preceding two months to be positively and significantly correlated with west Greenland coastal air temperature variations. Composites here are constructed over a similar two-month (60-day) period with data additionally sub-divided into 60-31 day (i.e. [-60,-31]) and 30-1 day (i.e. [-30,-1]) bins preceding each Baffin Bay DOA from 2011 to 2015. A paucity of T+ events over the 30 days post-Baffin DOA limits analyses to the aforementioned periods before the development of extensive, seasonal sea ice coverage. Second, the technique is intended to isolate meteorological processes most common during KAN_B daily mean air temperature events of ≥0°C (T+) versus <0°C (T-). To resolve the spatial cohesiveness of melt events along the K-transect, daily mean air temperatures at each K-transect station are composited (i.e. averaged) for KAN_B T+ and T- days in the [-60,-31] and [-30,-1] periods. On average during 2011-2015, KAN_B T+ events characterize ~46% of days in the [-60,-31] period, while [-30,-1] events are less frequent and occur 9% of days preceding Baffin Bay DOA. T+ comparisons between KAN_B and other K-transect stations are provided in Table 2. Temporal overlap between above-freezing temperatures at KAN_B versus S5 (77%) and KAN_L (46%) in columns 2-3 of Table 2 suggest spatial coherence in the physical mechanisms forcing melt at least across part of the lower ablation area.

In a similar fashion to Carr et al. (2017), a Wilcoxon test is used to evaluate differences in atmospheric variables and indices between T+ versus T- events. This nonparametric test is intended for continuous data series that do not follow underlying assumptions of the normal distribution making it appropriate for comparative analyses between extreme and non-extreme conditions. The null hypothesis of no difference in atmospheric conditions between cases is rejected at the 95% confidence level when $p \leq 0.05$.

Following the methodology used in Mattingly et al. (2016, 2018), daily atmospheric moisture transport about Greenland is resolved from ERA-Interim data by calculating IVT_{\downarrow} as in Eq. (1):

$$IVT = \frac{1}{g} \int_{1000 \text{ hPa}}^{200 \text{ hPa}} qV dp \quad (1)$$

where g is gravitational acceleration, q is specific humidity, V is the vector wind (ms^{-1}), and dp represents the difference between atmospheric pressure levels. The percentile rank of IVT (IVT PR) within a 30-day moving window is calculated to account for the seasonal cycle of IVT, and IVT PR is then classified using the SOM technique to

Deleted: unseasonal

Deleted: First

Deleted: regional

Deleted: KAN_B is selected to build composite sizes as this location experiences more T+ events annually than any other PROMICE or IMAU AWS on the K-transect, and due to station's location near the ice margin along the transect (**Table 1**).

Deleted: the

Deleted: .

Deleted: The second limit involves the length of the analysis period prior to DOA. Through lead/lag correlations of recent data series of ≥30 years, Hanna et al. (2009) and Ballinger et al. (2018a) noted Baffin ice coverage and sea surface temperatures in the preceding two months to be positively and significantly correlated with west Greenland coastal air temperature variations. Composites here are constructed over a similar two-month (60-day) period with data additionally sub-divided into 60-31 day (i.e. D₆₀) and 30-1 day (i.e. D₃₀) bins preceding each Baffin DOA from 2011 to 2015. A paucity of T+ events over the 30 days post-Baffin DOA limits analyses to the aforementioned periods before the development of extensive, seasonal sea ice coverage.

Deleted: utilized

Deleted: integrated water vapor transport (

Deleted:)

produce a matrix of moisture transport patterns, or nodes, that typically occur over the Greenland region. The SOM is based on an unsupervised machine learning algorithm that classifies each daily IVT PR field into the closest matching SOM node. This study uses the same SOM dimensions, training parameters, and IVT composites as Mattingly et al. (2016). We further classify SOM nodes—based on visual inspection of IVT PR patterns over Greenland—into the same, “wet” (anomalously high IVT PR over Greenland), “neutral” (near climatological median values), and dry (anomalously low) SOM node groups as these authors, and test whether the frequency of IVT patterns falling into each node group differs across T+ and T- events.

4 Results

4.1 Characteristics of Baffin Bay and west Greenland late-season melt

Dates marking the end of the Northwest Atlantic melt season area are shown in **Fig. S1**. Slow, upward change signifying later sea ice formation is shown in the DOA series, particularly from around 2000. Meanwhile, the start of the last ≥ 3 -day sequence of Region 3 (west-central Greenland; see inset in **Fig. 1**) 2% or 4% melt area also suggest progressively later melt (and a later onset of the freeze season). A significant break in the 2% series is highlighted by a drastic increase in variability from 1979–1999 ($\sigma=21.17$) to 2000–2015 ($\sigma=44.25$) that is also present in the annual discharge records from the nearby Watson River and Tasersiaq ice sheet catchments (Ahlström et al., 2017; van As et al., 2018). Differences between the beginning of Baffin Bay sea ice advance and the end of the ice sheet melt season have clearly narrowed, in part due to regional melt season lengthening. Some GrIS melt events since 2000 have notably occurred after seasonal sea ice formation (i.e. 2002, 2004–2005, 2010).

Relative to the climatology defined as 1981–2010, sea ice advanced ~ 11 d earlier in 2011 and ~ 6 d later in 2012–2015 (**Table S1**). Inspection of DOA for individual grid cells adjacent to the Sisimiut AWS (WMO code 4234 in **Fig. 1**), located ~ 150 km west of the K-transect ice sheet margin, reveals a northward-extending notch where ice forms ~ 30 – 60 d later than the Baffin-wide DOA (**Fig S2a-e**; **Fig S3**). Interannual differences in ice cover advance often depend on factors including regional winds, ocean heat transport, and water-mass changes (Myers et al., 2009; Ribergaard, 2014). For instance, strong offshore winds and poleward circulation of warm water from the West Greenland Slope Current (WGSC) often contribute to the local open water persistence, while southward Arctic Water transports support earlier ice formation patterns found in the east and north (Curry et al., 2014).

4.2 Local meteorology of melt versus non-melt cases

The spatial coherence of AWS observations across the K-transect along with inhomogenous GrIS Region 3 spatial melt patterns (e.g. southern GrIS pixels may pick up melt while those to the north do not experience the same conditions) and satellite pixel contamination issues at the tundra-ice interface, lead us to assess the melt events at the station level. Composites of air temperature, wind speed and direction by KAN_B T+ and T- events are shown in **Fig. 2**. Across the transect, composite air temperature differences (T+ versus T- events) are warmer by roughly 7 to 8°C in the [-60,-31] window and 12 to 13°C in the [-30,-1] period (**Fig. 2a**). These differences tend to be least near the coast and increase to S6 in the mid-ablation area (~ 1000 m asl) where contemporaneous melt occurs ~ 14 – 16% of the time (**Table 2**).

Wind direction for T+ events are roughly southeasterly ($<150^\circ$) in [-60,-31] and become more southerly (180°) in the [-30,-1] period (**Fig. 2c**) regardless of the wind speed (**Fig. 2b,d**). Above the long-term equilibrium line

Deleted: A

Deleted: in

Deleted: , similar

Deleted: are aggregated, then their frequencies are composited and tested following methods previously summarized.

Deleted:

Deleted: Perspectives on

Deleted: s

Deleted: s

Deleted: .

Deleted: and s

Deleted: than the mean date

Deleted: D₆₀

Deleted: D₃₀

Deleted: is consistently SSE

Deleted: D₆₀

Deleted: comparatively

Deleted: s

Deleted: slightly

Deleted: D₃₀

290 altitude, S9 [-60,-31] and KAN_U [-30,-1] winds are significantly more southerly during T+ events. These katabatic winds are deflected to the right (southeasterly) by the Coriolis force as they travel toward Baffin Bay (van den Broeke et al., 2009) and may be aided additionally by synoptically-driven southerly winds. There is also evidence of wind speed intensification during [-60,-31] T+ events (~1–2 ms⁻¹) and to a lesser magnitude similar relationships hold during the [-30, -1] period (Fig. 2b). Increased wind speeds in T+ versus T- events are likely affected by the seaward enhancement of the pressure gradient aided by nearshore open water persistence (Fig. S4), while increased synoptic cyclone activity and lower MSLP over Baffin Bay during the summer-autumn season transition may also enhance offshore flows (McLeod and Mote, 2015). Wind speed increases may also initiate positive (downward) sensible heat fluxes associated with low elevation ice melt (Fig. S5). Just offshore, sensible and latent fluxes are generally negative in T- events and near zero to slightly positive in melt occurrences with large, positive differences in T+ vs T- events apparent in oceanic areas from the Labrador Sea extending up to the WGSC (Figs. S5 and S6).

300 The K-transect offshore flows appear to represent a dynamic barrier to Baffin Bay marine layer intrusions. To further examine lower tropospheric flow across the ocean-land-ice interface, we similarly composite MAR and RACMO2 winds at 10-m and 850 hPa (Figs. 3 and 4). In general, the MAR and RACMO2 winds show directional consistency with overlaid PROMICE and IMAU winds with a slight southerly bias in both products for [-30,-1] at KAN_M and S9 in the upper ablation area. Simulated wind speeds are ~20-50% stronger during T+ versus T- events (not shown) as corroborated by most of the AWS observations (Fig. 2b). T+ events in RACMO2 and MAR generally capture AWS observed wind speeds in the upper ablation area at KAN_M (r²≥0.77) and lower accumulation area at KAN_U (r²≥0.77) with low root mean squared errors (RMSE<1.50 in all cases). A slight, positive bias in model-derived wind speed is evident at the ice sheet edge near KAN_B (MAR r²= 0.33, RACMO2 r²= 0.58). We note that height and therefore surface roughness differences between the AWS measurements (2–3 m) and regional model 10-m winds may explain a portion of the bias at KAN_B. Except during [-30,-1] T+ events, the 10-m winds extending about the transect from the west coast tundra just offshore and into eastern Baffin Bay are notably calm and alongshore (i.e. northerly in T- and southerly in T+; Figs. 3 and 4).

4.3 The role of North Atlantic atmospheric patterns

315 Overplots of 500 hPa GPH, 1000-700 hPa mean wind, and IVT for Greenland and the surrounding northwest Atlantic region are shown in Fig. 5. Whereas T- events tend to be characterized by northerly winds over the 1000-700 hPa layer, the T+ events indicate southerly, on-ice transfer of subpolar air aided by the presence of an upper-level trough over Baffin Island and downwind ridging over Greenland (see left versus right panel plots in Fig. 5, respectively). Comparatively higher GPH values are found over the ice sheet with the 540 dam (i.e. 5400 m) contour, which tends to distinguish solid and liquid precipitation, extending across central Greenland in T+ events, but located south of the island in T- events. In both T+ cases, 1000-700 winds circulate poleward over north Labrador Sea areas of upward, turbulent heat flux (Figs. S5 and S6), aiding the heat and moisture transfer (as shown by heightened IVT values in T+ relative to T-) to the western Greenland ice sheet during [-60,-31] and [-30,-1] (Fig. 5). Local IVT maxima in both events are concentrated over the southwest tip of the island, but remain ~100 kg m⁻¹ s⁻¹ or higher near the K-transect. Comparatively, depth integrated moisture flux over much of the west coast increases by a factor of 2–

- Deleted: Differences in wind direction do not strongly change by temperature regime, but t
- Deleted: slight
- Deleted: D₆₀
- Deleted: D₃₀
- Deleted:
- Deleted: s reflect strengthened ESE katabatic flows as
- Deleted: result of
- Deleted: (not shown)
- Deleted: from
- Formatted: Font: Bold
- Deleted: ,
- Deleted: upward
- Deleted: and convective boundary layer intensification
- Deleted: 4
- Deleted: 4
- Deleted: 5
- Deleted: 0
- Deleted: D₃₀
- Deleted: Modeled
- Deleted: more intense
- Deleted: in
- Formatted: Font: Bold
- Deleted: with pressure gradient enhancement, positive surface radiative balance, and katabatic (or glacier) wind presence near the [1]
- Deleted: zone
- Deleted: zone
- Deleted: not shown
- Deleted: both models
- Deleted: H
- Deleted: outputs (
- Deleted:)
- Deleted: D₃₀
- Deleted: Composites of the AWS K-transect observations and, [2]
- Deleted: the
- Deleted: N
- Deleted: (left panels)
- Deleted: (right panels)
- Formatted ... [3]
- Deleted: low-level
- Deleted: 4
- Deleted: 5
- Deleted: over
- Deleted: D₆₀
- Deleted: D₃₀

375 3 (4–5) during [-60,-31], (-30,-1) T+ versus T- events signaling a concentration of moist, onshore flow and
condensational processes over the ice sheet that drive the above-freezing air temperatures.

To further characterize and differentiate weather conditions by T± event, we composite SOM-classified daily
IVT wet, dry, and neutral patterns identified by Mattingly et al. (2016). Analyses of the aggregated frequencies
suggest that the wet patterns (with anomalously high IVT versus climatology) occur significantly more often in T+
380 versus T- events, and such nodes are more common by a factor of >4.5 in the [-30,-1] period. (Fig. 6a). While some
caution should be exercised as the absolute frequency of these patterns decreases from roughly early ([-60,-31]) to late
([-30,-1]) autumn, humid atmospheric conditions appear to enhance late-season melt. Increased incidence of wet
patterns coincides with negative (positive) NAO (GBI) (both >|0.50| in T+ events; Fig. 6b), and a synoptic
environment characterized by high surface (upper-level) pressure anomalies. This is confirmed by Fig. 5 whereby the
385 higher 500 GPH values and 1000-700 mean winds during T+ events transport warm and moist air masses from
Labrador Sea and southerly maritime latitudes to much of the western slope of the ice sheet to facilitate ablation-area
melt.

5 Discussion

West Greenland summer and autumn air temperature variability and trends during the last 3–4 decades have
390 shown strong response to increased frequency and intensity of Greenland high-pressure blocking, negative NAO
patterns, and positive North Atlantic SST anomalies, aided by background anthropogenic forcing (Hanna et al., 2016;
McLeod and Mote, 2016; Ballinger et al., 2018a; Graeter et al., 2018). The current North Atlantic “warm period”
since the mid-1990s is characterized by a positive Atlantic Multidecadal Oscillation phase and rising SSTs around
southwestern Greenland (Myers et al., 2009; Ribergaard, 2014), including just offshore of Sisimiut (WMO code 4234
395 in Fig. 1) (orthogonal trend = +0.03°C year⁻¹, p<0.05, for 1995-2015 period using SST product described in Ballinger
et al., 2018b). Warming waters around the island are influencing Baffin Bay sea ice and west GrIS melt processes
(Hanna et al., 2013; McLeod and Mote, 2015; Ballinger et al., 2018a) and seasonality toward earlier melt and later
freeze (Stroeve et al., 2017). This melt area about K-transect suggests local low SIC and open water, inferred upward
turbulent atmospheric heating, and onshore winds, could influence nearby terrestrial melt events. Moreover, Sisimiut
400 SSTs fluctuate with air temperatures (over the 60 days preceding DOA) in a statistically significant fashion for 2013-
2015 at most K-transect stations with some distance decay noted upslope from the edge of the ablation area at S9 (Fig.
S6). Summer and autumn west Greenland near-coastal air temperatures are modulated by the thermal properties of
bordering SSTs (Hanna et al., 2009; Ballinger et al., 2018a). Interannual differences in the strength of SST-air
temperature relationships (i.e. 2013–2015 versus 2011–2012) suggest: 1) processes driving warming ocean waters and
405 air temperatures over the GrIS are independent when disparate wind directions occur at or near the ocean-tundra-ice
sheet boundaries in years of weak-to-zero correlation (e.g. katabatic flows contrasting near-coastal barrier flows (van
den Broeke and Gallée, 1996)), or alternatively 2) large-scale atmospheric circulation forcing (i.e. near-surface and
upper-level meridional winds), during years of positive, statistically significant correlations, modulates the near-shore
surface open water and ice sheet air temperatures (Stroeve et al., 2017). We recognize that synoptic patterns may not
410 necessarily be mutually exclusive in these examples, but the manuscript objectives do not include comparison of high
and low pressure features around Greenland for specific melt and non-melt events.

Deleted: D₆₀

Deleted: D₃₀

Deleted: s

Deleted: D₃₀

Deleted: D₆₀

Deleted: D₃₀

Deleted: unseasonal

Deleted: on-ice lower tropospheric

Deleted: in

Deleted: intensity

Deleted: s

Deleted: (later)

Deleted: (

Deleted:)

Deleted: hotspot of

Deleted: /or

Deleted: and

Deleted: atmospheric

Deleted: As shown in Fig. S6,

Deleted: toward

Deleted: zone

Deleted: have been shown to be

Deleted: strong

Deleted: in

Deleted: often

Deleted: robust

Deleted: -variability

Deleted: (i.e. near-surface and upper-level meridional winds)

440 A number of studies have suggested that Baffin Bay marine layer interaction with the ice sheet boundary layer is obstructed by zonal and meridional flows such as the west coast plateau jet feature and katabatic winds (Hanna et al., 2009; Moore et al., 2013; Noël et al., 2014). Moore et al. (2013) noted a directionally consistent southerly 10-m wind field extending over the western half of Greenland in summer and winter, while observational studies similarly indicate a high frequency of southerly-to-southeasterly winds over the K-transect (van den Broeke et al., 2009).
 445 Southerly (easterly) 10-m winds are strongly linked to melt across two thirds (the southern third) of the ice sheet (Cullather and Nowicki, 2018). For an expanded spatial perspective, we briefly examine air temperatures at the next PROMICE station installment approximately 700 km north at Upernavik (UPE; 72.89°N). We find UPE_L (220 m asl on the ice sheet) melt occurs the day of KAN_B T+ events on >50% of occasions in both [-60,-31] and [-30,-1] windows (not shown). This suggests that above-freezing near-surface air often penetrates at least to PROMICE station UPE_L with a relatively warm air mass engulfing much of the west coast. Our observational and regional model analyses further show that homogenous low-level winds extend coastward at least to the tundra-ice sheet interface near KAN_B (see Figs. 2c, 3, and 4) and produce a “blocking effect” that inhibits the inland penetration of near-surface air from Baffin Bay (Noël et al., 2014). Of note, the katabatic mechanism becomes stronger as Baffin Bay DOA approaches in late autumn, with more pronounced radiational cooling over the ice sheet further supporting winds that prevent incursions of local marine air (van As et al., 2014).
 455 If late season K-transect melt is minimally influenced by local Baffin Bay open water, then what physical mechanisms drive the melt events? Composites of the AWS K-transect observations and complementary regional model output indicate that recent late-season melt events tend to be driven by southerly synoptic patterns as opposed to local marine forcing. We provide evidence of this physical forcing by [-60,-31] and [-30,-1] T+ composites that show southerly flows of more warm, moist maritime air of lower latitude origins relative to T- cases. As shown in Fig. 5, during the former event period, air is transferred off northern Labrador Sea to the west coast, while a path of more southerly flow directs moist North Atlantic air masses onto Baffin Bay and southwestern Greenland in the period immediately preceding DOA. These “wet” synoptic patterns occur frequently under anomalous (>|1σ) positive GBI and negative NAO values (Fig. 6a, b). We surmise from Mattingly et al. (2018) that such patterns are particularly moisture-rich (≥85th percentile IVT climatological values) and often accompanied by atmospheric rivers impacting Greenland, and their occurrence causes ablation area melt in non-summer, low insolation months through cloud radiative effects (i.e. increased downward longwave radiation transfer into the ice surface), condensational latent heat release, and liquid precipitation (Doyle et al., 2015; Binder et al., 2017; Oltmanns et al., 2019). The southerly winds that propagate moisture northward off the northwestern Atlantic Ocean are a product of amplified upper-level geopotential height patterns and meridional winds in T+ versus T- events extending from Denmark Strait and Irminger Sea on the east coast of Greenland onto the ice sheet (Fig. 5). Mid-tropospheric ridging, which is more pronounced in [-30,-1] than [-60,-31] events, supports southerly winds that funnel heat and moisture from likely deeper in the Atlantic basin to Baffin Bay and southwest Greenland to stimulate sea ice and GrIS ablation area melt conditions (Ahlstrøm et al., 2017; Ballinger et al., 2018a,b; Hanna et al., 2018). Cullather and Nowicki (2018) similarly find collocated, positive surface and 500 hPa GPH anomalies over Denmark Strait and Irminger Sea tend to be associated with melt events in the basin encompassing the K-transect. Our analyses support North Atlantic-air-ice sheet coupling,
 475

- Deleted: D₆₀
- Deleted: D₃₀
- Deleted: air
- Deleted: wind
- Deleted: and therefore
- Deleted: more
- Deleted: active of
- Deleted: influence
- Deleted: with increased radiative cooling toward the Baffin DOA and continuous freeze period in climatological winter
- Deleted: does not appear to be driven by a
- Deleted: influence
- Deleted: show
- Deleted: that T+ events
- Deleted: D₆₀
- Deleted: D₃₀
- Deleted: partitions are
- Deleted: characterized by
- Deleted: (negative)
- Deleted: (
- Deleted:)
- Deleted: zone
- Deleted: 8
- Deleted: s
- Deleted: D₃₀
- Deleted: across

rather than localized Baffin Bay ocean-atmosphere processes, as a strong driver of transition season melt before sea ice advances south of the K-transect. Synoptic patterns associated with negative summer NAO and positive GBI incidence strongly influence these melt events (Fig. 6), prompting decreases in SMB, and increase in the K-transect equilibrium line altitude over the last 10-15 years (Hanna et al., 2013; Smeets et al., 2018).

6 Conclusions

Temporal co-variability between GrIS and Arctic sea ice mass loss suggests a possible feedback whereby adjacent open water conditions, ocean-to-atmosphere heat flux, and on-ice winds affect inland melt during the end of the melt season. In our 2011–2015 analyses bridging the end-of-summer/early autumn melt to the date of first-year Baffin Bay sea ice advance, we find no evidence to support the hypothesis that local open water, resultant turbulent heating, and onshore winds have a pronounced impact on inland ice melt events. These thermodynamic processes, in particular, directly influence coastal air temperatures and have a fingerprint on marine outlet glacier behaviors (Carr et al., 2017), but are shown here to be inhibited by topographically-influenced flows and synoptic patterns whose interactions are not mutually exclusive. Furthermore, Baffin Bay warming coupled with a longer autumn open water period has been hypothesized to stimulate and invigorate upper-level, high-pressure blocking that promotes southerly air advection over the west Greenland coast (Ballinger et al., 2018a). This is consistent with the main conclusions of Noël et al. (2014), which suggest that while warming waters around Greenland minimally affect SMB beyond enhancing tidewater glacier retreat rates SST forcing may indirectly influence GrIS SMB changes through impacts on atmospheric circulation. However, in terms of direct forcing by the local marine layer, beyond a near-coastal influence, our AWS, regional, and synoptic wind analyses suggest that Baffin Bay does not represent a substantial advective heat and moisture source to the ice sheet during our 5-year analyses.

Future late season analyses, perhaps reconstructing K-transect meteorological conditions back to the origins of the modern sea ice record, might be insightful in comparing local ocean-ice sheet interactions spanning the 1990s shift from colder to warmer Baffin Bay summer SSTs (Ballinger et al., 2018a). Assessing the temperature and pressure gradients and their vertical profiles derived from retrospective analyses would also be useful to categorize the structure, magnitude, and direction of regional winds, including the katabatic regime, in attempting to provide a longer-term perspective of analyses presented in this paper. Noël et al. (2014) hypothesized that future sea-surface warming may exacerbate the division between local ocean and ice sheet by intensifying the temperature and pressure gradient and hence resulting katabatic winds. Baffin Bay climate and cryospheric changes in the last two decades suggest such an increased “blocking” mechanism may already be underway. Moreover, stronger katabatic winds might be enhanced further by an increasing intensity of autumn mid-troposphere high-pressure over Greenland (Hanna et al., 2018a, see their Fig. 1e). Synergistic future research should continue to monitor the spatial extent, drivers, and physical effects of late-season melt through observational products and regional modeling tools, including quantification of late season K-transect mass loss and runoff through the Watson River, contributions to subsurface/firn processes, and preconditioning effects on the following year’s melt season.

Author Contributions. TJB and TLM conceived the study. TJB analyzed the observational data, with assistance from MP and SG, and led the writing of the manuscript. TLM developed and processed the satellite-derived GrIS melt data. KSM conducted the IVT classification and assisted with the creation of several figures. ACB developed the

Deleted: summer (Rennermalm et al., 2009; Liu et al., 2016) and

Deleted: around the limits

Deleted: (Stroeve et al., 2017)

Deleted: and

Deleted: s

Deleted: demonstrable

Deleted: e

Deleted: effect

Deleted: Thus

Deleted: we find

Deleted: n

Deleted: T

Deleted: unseasonal

DOA series and contributed related figures. EH provided the daily GBI series, and DvA, [CHR_PCJPS](#), MHR, and JC provided AWS or oceanographic data and support. BN and XF developed and processed regional model wind fields for RACMO2.3p2 and MAR v3.9, respectively. All authors provided valuable insights, feedback, and editing on manuscript drafts.

Acknowledgements. The KAN PROMICE weather stations are funded by the Greenland Analogue Project, and the IMAU K-transect stations are funded by the Netherland Institute for Scientific Research and its Netherlands Polar Programme. TJB acknowledges support from Texas State University, and IASC, NSF, and UAF for sponsoring and facilitating an APECS travel grant to attend the POLAR 2018 Open Science Conference where valuable project-related feedback was received. BN acknowledges funding from the Polar Program of the Netherlands Organization for Scientific Research (NWO) and the Netherlands Earth System Science Centre (NESSC). The authors thank David Bromwich and Jeffrey Miller for constructive comments on early results, and Thomas Cropper for making available his daily NAO series. Constructive remarks from Charalampos Charalampidis and two anonymous references were helpful in guiding manuscript improvements.

Deleted: also

References

- 570 Ahlstrom, A.P., Petersen, D., Langen P.L., Citterio, M., and Box, J.E.: Abrupt shift in the observed runoff from the southwestern Greenland ice sheet. *Sci. Advan.*, 3, 1-7, doi:10.1126/sciadv.1701169, 2017.
- Ballinger, T.J., Hanna, E., Hall, R.J. Miller, J., Ribergaard, M.H., and Høyer, J.L.: Greenland coastal air temperatures linked to Baffin Bay and Greenland Sea ice conditions during autumn through regional blocking patterns. *Clim. Dyn.*, 50, 83-100, doi:10.1007/s00382-017-3583-3, 2018a.
- 575 Ballinger, T.J., Hanna, E., Hall, R.J., Miller, J., Ribergaard, M.H., Overland, J.E., and Høyer, J.L.: Anomalous blocking over Greenland preceded the 2013 extreme early melt of local sea ice. *Ann. Glaciol.*, 59, 181-190, doi:10.1017/aog.2017.30, 2018b.
- Bamber, J.L., Westaway, R.M., Marzeion, B. and Wouters, B.: The land ice contribution to sea level during the satellite era. *Environ. Res. Lett.* 13, 063008, doi:10.1088/1748-9326/aac2f0, 2018.
- 580 Binder, H., Boettcher, M., Grams, C.M., Joos, H., and Wernli, H.: Exceptional air mass transport and dynamical drivers of an extreme wintertime Arctic warm event. *Geophys. Res. Lett.*, 44, 12028-12036, doi:10.1002/2017GL075841, 2017.
- Bliss, A. C., Steele, M., Peng, G., Meier, W.N., and Dickinson, S.: Regional variability of Arctic sea ice seasonal change climate indicators from a passive microwave climate data record. *Environ. Res. Lett.*, 14, 4, doi:10.1088/1748-9326/aafb84, 2019.
- 585 Bromwich, D.H., Wilson, A.B., Bai, L.-S., Moore, G.W.K., and Bauer, P.: A comparison of the regional Arctic System Reanalysis and the global ERA-Interim Reanalysis for the Arctic. *Q.J.R. Meteorol. Soc.*, 142, 644-658, doi:10.1002/qj.2527, 2016.
- Cappelen, J.: Weather observations from Greenland 1958-2017. Observation data with description. DMI Report 18-08. Copenhagen, Denmark, 2018.
- 590 Cappelen, J.: Weather observations from Greenland 1958-2018. Observation data with description. DMI Report 19-08. Copenhagen, Denmark, 2019, in preparation.
- Carr, J.R., Stokes, C.R., and Vieli, A.S.: Threefold increase in marine-terminating outlet glacier retreat rates across the Atlantic Arctic: 1992-2010. *Ann. Glaciol.*, 58, 72-91, doi:10.1017/aog.2017.3, 2017.
- 595 [Charalampidis, C., van As, D., Box, J. E., van den Broeke, M. R., Colgan, W. T., Doyle, S. H., Hubbard, A. L., MacFerrin, M., Machguth, H., and Smeets, C. J. P. P.: Changing surface-atmosphere energy exchange and refreezing capacity of the lower accumulation area, West Greenland. *The Cryosphere*, 9, 2163-2181, doi:10.5194/tc-9-2163, 2015.](#)
- Cropper, T., Hanna, E. Valente, M.A., and Jónsson, T.: A daily Azores-Iceland North Atlantic Oscillation index back to 1850. *Geosci. Data J.*, 2, 12-24, doi:10.1002/gdj3.23, 2015.
- 600 Cullather, R.I., and Nowicki, S.M.J.: Greenland ice sheet surface melt and its relation to daily atmospheric conditions. *J. Clim.*, 31, 1897-1919, doi:10.1175/JCLI-D-17-0447.1, 2018.
- Curry, B. Lee, C.M., Petrie, B., Moritz, R.E., and Kwok, R.: Multiyear volume, liquid freshwater, and sea ice transports through Davis Strait, 2004-2010. *J. Phys. Oceanog.*, 44, 1244-1266, doi:10.1175/JPO-D-13-0177.1, 2014.

Deleted: V

Deleted: S

Deleted: I

Deleted: S

Deleted: C

Deleted: C

Deleted: I

Deleted: P

Deleted: M

Deleted: C

Deleted: D

Deleted: R

Deleted: S

Deleted: in review

Formatted: Normal (Web), Left, Widow/Orphan control, Adjust space between Latin and Asian text, Adjust space between Asian text and numbers, Pattern: Clear (White)

Formatted: Font: Times, Font color: Auto

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A.,
620 Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C.,
Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, I.,
Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.K.,
Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., Vitart, F.: The ERA-Interim reanalysis: configuration
and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.*, 137, 553–597, doi:10.1002/qj.828,
625 2011.

Delhasse, A., Fettweis, X., Kittel, C., Amory, C., and Agosta, C.: Brief communication: Impact of the recent
atmospheric circulation change in summer on the future surface mass balance of the Greenland Ice Sheet,
Cryosphere, 12, 3409-3418, doi:10.5194/tc-2018-65, 2018.

Doyle, S., Hubbard, A., van de Wal, R.S., Box, J., van As, D., Scharrer, K., Meierbachtol, T.W., Smeets, P.C.J.P.,
630 Harper, J.T., Johansson, E., Mottram, R.H., Mikkelsen, A.B., Wilhelms, F., Patton, H., Christoffersen, P.,
Hubbard, B.: Amplified melt and flow of the Greenland ice sheet driven by late-summer cyclonic rainfall. *Nat.*
Geosci. 8, 647-653, doi:10.1038/ngeo2482, 2015.

Fettweis, X., Tedesco, M., van den Broeke, M., and Ettema, J.: Melting trends over the Greenland ice sheet (1958–
2009) from spaceborne microwave data and regional climate models, *Cryosphere*, 5, 359-375, doi:10.5194/tc-5-
635 359, 2011.

Fettweis, X., Box, J. E., Agosta, C., Amory, C., Kittel, C., Lang, C., van As, D., Machguth, H., and Gallée, H.:
Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR
model, *Cryosphere*, 11, 1015-1033, doi:10.5194/tc-11-1015, 2017.

Graeter, K.A., Osterberg, E.C., Ferris, D.G., Hawley, R.L., Marshall, H.P., Lewis, G., Meehan, T., McCarthy, F.,
640 Overly, T., and Birkel, S.D.: Ice core records of west Greenland melt and climate forcing. *Geophys. Res. Lett.*,
45, 3164-3172, doi:10.1002/2017GL076641, 2018.

Graham, R.M., Cohen, L., Petty, A.A., Boisvert, L.N., Rinke, A., Hudson, S.R., Nicolaus, M., and Granskog, M.A.:
Increasing frequency and duration of Arctic winter warming events. *Geophys. Res. Lett.*, 44, 6974-6983,
doi:10.1002/2017GL073395, 2017.

645 Hanna, E., Cappelen, J., Fettweis, X., Huybrechts, P., Luckman, A., and Ribergaard, M.H.: Hydrologic response of the
Greenland ice sheet: the role of oceanographic warming. *Hydrol. Proc.*, 23, 7-30, doi:10.1002/hyp.7090, 2009.

Hanna, E., Mernild, S.H., Cappelen, J., and Steffen, K.: Recent warming in Greenland in a long-term instrumental
(1881-2012) climatic context: I. Evaluation of surface air temperature records. *Environ. Res. Lett.*, 7, 1-15,
doi:10.1088/1748-9326/7/4/045404, 2012.

650 Hanna, E., Jones, J.M., Cappelen, J., Mernild, S.H., Wood, L., Steffen, K., and Huybrechts, P.: The influence of North
Atlantic atmospheric and oceanic forcing effects on 1900-2010 Greenland summer climate and ice melt/runoff.
Int. J. Climatol., 33, 862-880, doi:10.1002/joc.3475, 2013.

Hanna, E., Fettweis, X., Mernild, S.H., Cappelen, J., Ribergaard, M.H., Shuman, C.A., Steffen, K., Wood, L., and
Mote, T.L.: Atmospheric and oceanic climate forcing of the exception Greenland ice sheet surface melt in
655 summer 2012. *Int. J. Climatol.*, 34, 1022-1037, 2014.

- Hanna, E., Cropper, T.E., Hall, R.J., and Cappelen, J.: Greenland Blocking Index 1851–2015: a regional climate change signal. *Int. J. Climatol.*, 36, 4847–4861, doi:10.1002/joc.4673, 2016.
- Hanna E., Hall, R.J., Cropper, T.E., Ballinger, T.J., Wake, L., Mote, T., and Cappelen, J.: Greenland Blocking Index daily series 1851-2015: analysis of changes in extremes and links with North Atlantic and UK climate variability and change. *Int. J. Climatol.*, 38, 3546-3564, doi:10.1002/joc.5516, 2018a.
- 660 Hanna, E., Fettweis, X., and Hall, R.J.: Brief communication: Recent changes in summer Greenland blocking captured by none of the CMIP5 models. *Cryosphere*, 12, 3287-3292, doi:10.5194/tc-12-3287, 2018b.
- Holland, D.M., Thomas, R.H., de Young, B., Ribergaard, M.H., and Lybert, B.: Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. *Nat. Geoscience*, 1, 659-664, doi:10.1038/ngeo316, 2008.
- 665 Markus, T., Stroeve, J. C., and Miller, J.: Recent changes in Arctic sea ice melt onset, freeze-up, and melt season length. *J. Geophys. Res.*, 114, C12024, doi:10.1029/2009JC005436, 2009.
- Mattingly, K.S., Ramseyer, C.A., Rosen, J.J., Mote, T.L., and Muthyala, R.: Increasing water vapor transport to Greenland Ice Sheet revealed using self-organizing maps. *Geophys. Res. Lett.*, 43, 9250-9258, doi:10.1002/2016GL070424, 2016.
- 670 Mattingly, K.S., Mote, T.L., and Fettweis, X.L.: Atmospheric river impacts on Greenland ice sheet surface mass balance. *J. Geophys. Res. Atmos.*, 123, 8538-8560, doi:10.1029/2018JD028714, 2018.
- McLeod, J.T., and Mote, T.L.: Assessing the role of precursor cyclones on the formation of extreme Greenland blocking episodes and their impact on summer melting across the Greenland ice sheet. *J. Geophys. Res.*, 120, 12357-12377, doi:10.1002/2015JD023945, 2015.
- 675 McLeod, J.T., and Mote, T.L.: Linking interannual variability in extreme Greenland blocking episodes to the recent increase in summer melting across the Greenland ice sheet. *Int. J. Climatol.*, 36, 1484-1499, doi:10.1002/joc.4440, 2016.
- Meier, W., Fetterer, F., Savoie, M., Mallory, S., Duerr, R., and Stroeve, J.: NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 3, Revision 1, National Snow & Ice Data Center, Boulder, Colorado (Accessed 18 December 2017), doi:http://dx.doi.org/10.7265/N59P2ZTG, 2017.
- 680 Mernild, S.H., Hanna, E., Yde, J.C., Cappelen, J., and Malmros, J.K.: Coastal Greenland air temperature extremes and trends 1890-2010: annual and monthly analysis. *Int. J. Climatol.*, 34, 1472-1487, doi:10.1002/joc.3777, 2014.
- Moore, G.W.K., Renfrew, I.A., and Cassano, J.J.: Greenland plateau jets. *Tellus A*, 65, 1748, 1-16, doi:10.3402/tellusa.v65i0.17468, 2013.
- 685 Moore, G.W.K.: The December 2015 North Pole Warming Event and increasing occurrence of such events. *Sci. Rep.*, 6, 39084, doi:10.1038/srep39084, 2016.
- Mote, T.L.: Greenland surface melt trends 1979-2007: Evidence of a large increase in 2007. *Geophys. Res. Lett.*, 34, L22507, doi:10.1029/2007GL0311976, 2007.
- Mote, T. L.: MEaSUREs Greenland Surface Melt Daily 25km EASE-Grid 2.0, Version 1. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi:10.5067/MEASURES/CRYOSPHERE/nsidc-0533.001. Accessed 1 September 2017, 2014.
- 690

Deleted: Liu, J., Chen, Z., Francis, J., Song, M., Mote, T., and Hu, Y: Has Arctic sea ice loss contributed to increased surface melting of the Greenland ice sheet? *J. Clim.*, 29, 3373-3386, doi:10.1175/JCLI-D-15-0391.1, 2016.

Myers, P.G., Donnelly, C., and Ribergaard, M.H.: Structure and variability of the west Greenland Current in summer derived from 6 repeat standard sections. *Prog. Ocean.*, 80, 93-112, doi:10.1016/j.pocean.2008.12.003, 2009.

Noël, B., Fettweis, X., van de Berg, W.J., van den Broeke, M.R., and Erpicum, M.: Sensitivity of Greenland Ice Sheet surface mass balance to perturbations in sea surface temperature and sea ice cover: a study with the regional climate model MAR. *Cryosphere*, 8, 1871-1883, doi:10.5194/tc-8-1871, 2014.

700 Noël, B., van de Berg, W.J., van Wessem, J.M., van Meijgaard, E., van As, D., Lenaerts, J.T.M., Lhermitte, S., Munneke, P.K., Smeets, C.J.P., van Ulft, L.H., van de Wal, R.S.W., and van den Broeke, M.R.: Modelling the climate and surface mass balance of the polar ice sheets using RACMO2 – Part 1: Greenland (1958 – 2016). *Cryosphere*, 12, 811-831, doi:10.5194/tc-12-811, 2018.

705 Ohmura, A., and Reeh, N.: New precipitation and accumulation maps for Greenland. *J. Glaciol.*, 37, 140-148, 1991.

Oltmanns, M., Straneo, F., and Tedesco, M.: Increased Greenland melt triggered by large-scale, year-round **cyclonic moisture intrusions**. *Cryosphere*, 13, 815-825, doi:10.5194/tc-13-815-2019, 2019.

Onarheim, I.H., Eldevik, T., Smedsrud, L.H., and Stroeve, J.C.: Seasonal and regional manifestation of Arctic sea ice loss. *J. Clim.*, 31, 4917-4932, doi:10.1175/JCLI-D-17-0427.1, 2018.

710 Overland, J.E., and Wang, M.: Recent extreme Arctic temperatures are due to a split polar vortex. *J. Clim.*, 29, 5609-5616, 2016.

Peng, G., Meier, W.N., Scott, D.J., and Savoie, M.H.: A long-term and reproducible passive microwave sea ice concentration data record for climate studies and monitoring. *Earth Syst. Sci. Data*, 5, 311-318, doi:10.5194/essd-5-311-2013, 2013.

715 Rennermalm, A.K., Smith, L.C., Stroeve, J.C., and Chu, V.W.: Does sea ice influence Greenland ice sheet surface-melt. *Environ. Res. Lett.*, 4, 1-6, doi:10.107282/T36D5RDG, 2009.

Ribergaard, M.H.: Oceanographic investigations off west Greenland 2013. NAFO Scientific Council Documents, 14/001, 2014.

Serreze, M.C., and Stroeve, J.: Arctic sea ice trends, variability and implications for seasonal forecasting. *Phil. Trans. R. Soc. A* 373: 20140159, 2015.

720 Smeets, P.C.J.P., Kuipers Munneke, P., van As, D., van den Broeke, M.R., Boot, W., Oerlemans, H., Snellen, H., Reijmer, C.H., and van de Wal, R.S.W.: The K-transect in west Greenland: Automatic weather station data (1993-2016). *Arc., Antarc., and Alp. Res.*, 50, S100002, doi:10.1080/15230430.2017.1420954, 2018.

725 Steele, M., Bliss, A.C., Peng, G., Meier, W.N. and Dickinson, S.: Arctic sea ice seasonal change and melt/freeze climate indicators from satellite data, Version 1, National Snow & Ice Data Center Distributed Active Archive Center, Boulder, Colorado, doi:10.5067/KINANQKEZI4T, 2019.

Straneo, F., and Heimbach, P.: North Atlantic warming and the retreat of Greenland's outlet glaciers. *Nature*, 504, 36-43, doi:10.1038/nature12854, 2013.

730 Stroeve, J.C., Mioduszewski, J.R., Rennermalm, A., Boisvert, L.N., Tedesco, M., and Robinson, D.: Investigating the local-scale influence of sea ice Greenland surface melt. *Cryosphere*, 11, 2363-2381, doi:10.5194/tc-11-2363, 2017.

Deleted: precipitation events

Deleted: Discuss.

Deleted: 1-18,

Deleted: 2018

Deleted: 243

Deleted: 8

Deleted: 1

Peng, G., Steele, M., Bliss, A.C., Meier, W.N., and Dickinson, S.: Temporal Means and Variability of Arctic Sea Ice Melt and Freeze Season Climate Indicators Using a Satellite Climate Data Record. *Remote Sens.*, 10, doi:10.3390/rs10091328, 2018.

[Stroeve, J.C., Schroder, D., Tsamados, M., and Feltham, D.: Warm winter, thin ice? *Cryosphere*, 12, 1791-1809, doi:10.5194/tc-12-1791, 2018.](#)

- 745 van As, D., Fausto, R.S., and PROMICE Project Team: Programme for Monitoring of the Greenland Ice Sheet (PROMICE): first temperature and ablation records. *Geol. Surv. Denmark Greenland Bull.*, 23, 73-76, 2011.
- van As, D., Fausto, R.S., Steffen, K., and PROMICE project team: Katabatic winds and piteraq storms: observations from the Greenland ice sheet. *Geol. Surv. Denmark Greenland Bull.*, 31, 83-86, 2014.
- 750 van As, D., Hasholt, B., Ahlstrøm, A.P., Box, J.E., Cappelen, J., Colgan, W., Fausto, R.S., Mernild, S.H., Mikkelsen, A.B., Noël, B.P.Y., Petersen, D., and van den Broeke, M.R., 2018: Reconstructing Greenland Ice Sheet meltwater discharge through the Watson River (1949-2017). *Arc., Antarc., and Alp. Res.*, 50, S100010, doi:10.1080/15230430.2018.1433799, 2018.
- van de Wal, R.S.W., Smeets, C.J.P.P., Boot, W., Stoffelen, M., van Kampen, R., Doyle, S.H., Wilhelms, F., van den Broeke, M.R., Reijmer, C.H., Oerlemans, J., and Hubbard, A.: Self-regulation of ice flow varies across the ablation area in south-west Greenland, *Cryosphere*, 9, 603-611, doi:10.5194/tc-9-603, 2015.
- 755 van den Broeke, M.R., and Gallée, H.: Observation and simulation of barrier winds at the western margin of the Greenland ice sheet. *Q.J.R. Meteorol. Soc.*, 122, 1365-1383, 1996.
- van den Broeke, M., Smeets, P., Ettema, J.: Surface layer climate and turbulent exchange in the ablation zone of the west Greenland ice sheet. *Int. J. Climatol.*, 29, 2309-2323, doi:10.1002/joc.1815., 2009.
- 760 van den Broeke, M.R., Enderlin, E.M., Howat, I.M., Kuipers Munneke, P., Noël, B.P.Y., van de Berg, W.J., van Meijgaard, E., and Wouters, B.: On the recent contribution of the Greenland ice sheet to sea level change. *Cryosphere*, 10, 1933-1946, doi:10.5194/tc-10-1933, 2016.
- van den Broeke, M., Box, J., Fettweis, X., Hanna, E., Noël, B., Tedesco, M., van As, D., van de Berg, W.J., van Kampenhout, L.: Greenland ice sheet surface mass loss: Recent developments in observation and modeling. *Curr. Clim. Change Rep.*, 3, 345-356, doi:10.1007/s40641-017-0084-8, 2017.
- 765

Formatted: Normal (Web), Adjust space between Latin and Asian text, Adjust space between Asian text and numbers

Deleted: Smeets, P.C.J.P., Kuipers Munneke, P., van As, D., van den Broeke, M.R., Boot, W., Oerlemans, H., Snellen, H., Reijmer, C.H., and van de Wal, R.S.W.: The K-transect in west Greenland: Automatic weather station data (1993-2016). *Arc., Antarc., and Alp. Res.*, 50, S100002, doi:10.1080/15230430.2017.1420954, 2018.[†]

Straneo, F., and Heimbach, P.: North Atlantic warming and the retreat of Greenland's outlet glaciers. *Nature*, 504, 36-43, doi:10.1038/nature12854, 2013.[†]

Stroeve, J.C., Mioduszewski, J.R., Rennermalm, A., Boisvert, L.N., Tedesco, M., and Robinson, D.: Investigating the local-scale influence of sea ice Greenland surface melt. *Cryosphere*, 11, 2363-2381, doi:10.5194/tc-11-2363, 2017.[†]

Stroeve, J.C., Schroder, D., Tsamados, M., and Feltham, D.: Warm winter, thin ice? *Cryosphere*, 12, 1791-1809, doi:10.5194/tc-12-1791, 2018.[†]

Tables

AWS Station	Network	Latitude (°N)	Longitude (°W)	Elevation (m asl)	Distance to/from terminus (km)
KAN_B	PROMICE	67.13	50.18	350	1
S5	IMAU	67.08	50.10	500	6
KAN_L	PROMICE	67.10	49.95	670	12
S6	IMAU	67.07	49.38	1000	37
KAN_M	PROMICE	67.07	48.84	1270	61
S9	IMAU	67.05	48.22	1500	88
KAN_U	PROMICE	67.00	47.03	1840	142

Formatted Table

785 **Table 1.** Summary details of the PROMICE and IMAU AWS stations utilized in this study, including their approximate geographic position (in decimal degrees), elevation, and distance from the ice sheet terminus moving west to east. KAN_B is located on the tundra, roughly 1 km east of the terminus. Distances are rounded to the nearest km as AWS sites are known to move ~50 - 150 m year⁻¹ (van de Wal et al., 2015).

790

AWS T Compare	T+ n[-60,-31]	T+ %[-60,-31]	T+ n[-30,-1]	T+ %[-30,-1]	T+ %[-60,-1]
S5 vs KAN_B	53	77	9	69	76
KAN_L vs KAN_B	32	46	8	62	49
S6 vs KAN_B	10	14	3	23	16
KAN_M vs KAN_B	2	3	1	8	4
S9 vs KAN_B	1	1	0	-	1
KAN_U vs KAN_B	0	-	0	-	-
Σ KAN_B T+ events	69	-	13	-	-

Formatted Table

795 **Table 2.** Counts of above-freezing daily mean air temperature (T+) events (n), 2011-2015, and the percentage of contemporaneous overlap (%) between T+ events at KAN_B and S5, KAN_L, S6, KAN_M, S9, or KAN_U. The [-60,-31] and [-30,-1] periods reference time windows before respective annual dates of Baffin Bay sea ice advance (DOA). As an example, 77% of the time in the 30 to 60-day (i.e. [-60,-31]) window preceding Baffin DOA, the T+ air temperature threshold at KAN_B is also observed at S5.

Deleted: Number

Deleted: when

Deleted:

Formatted: Underline

Deleted: measured T≥0°C (i.e. T+)

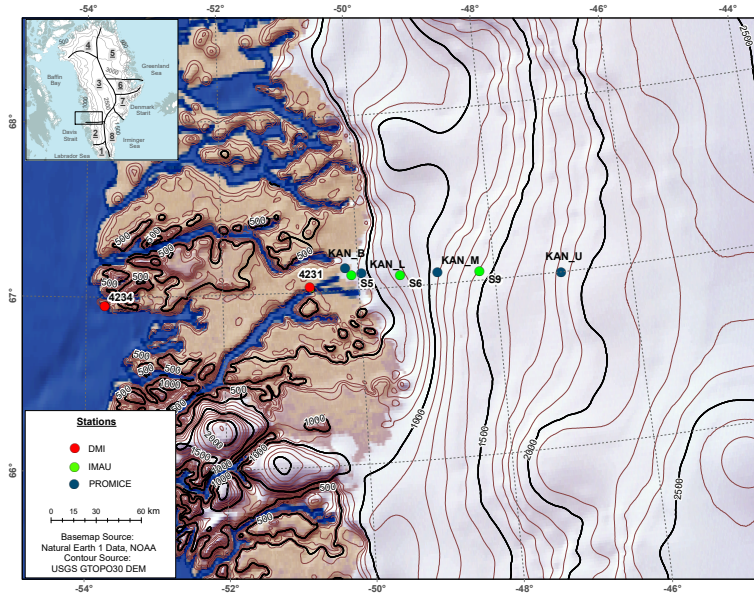
Deleted: For

Deleted: ice cover

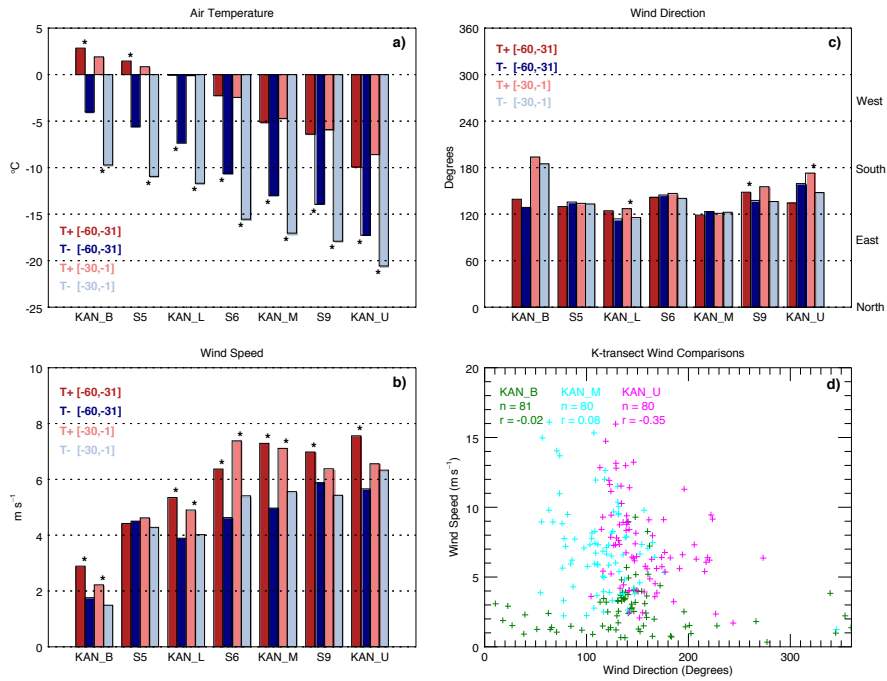
Deleted: ≥0°C

Deleted: The [-60,-31] and [-30,-1] periods reference time windows before respective annual dates of sea ice advance (DOA).

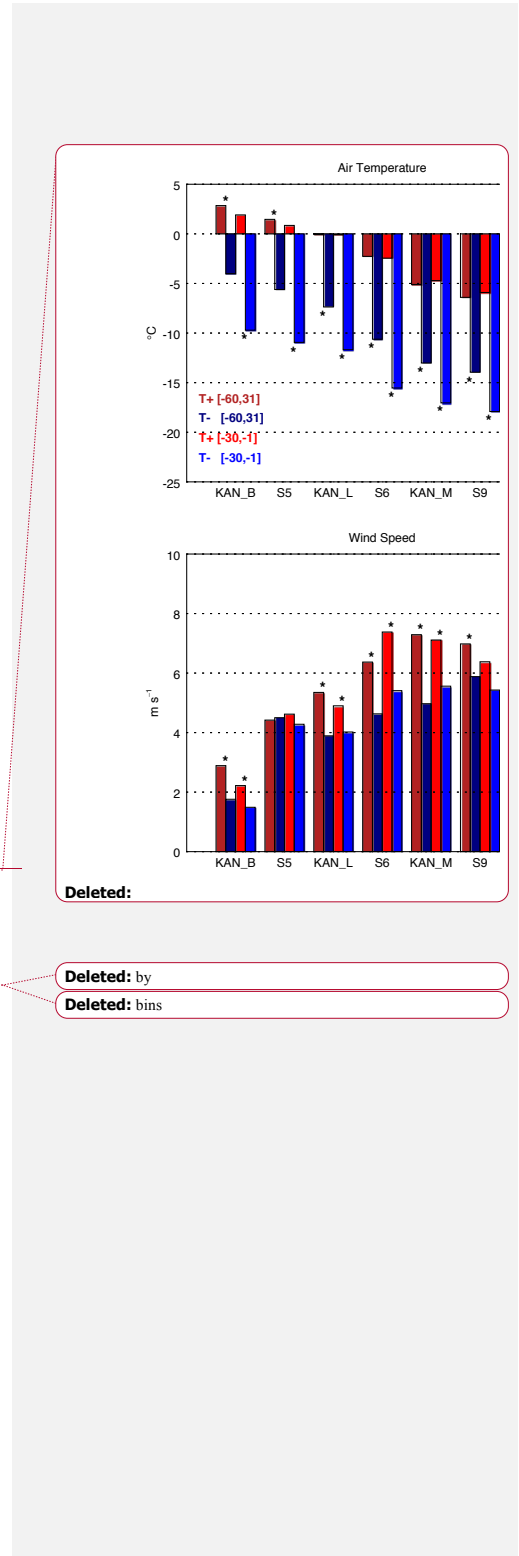
Figures



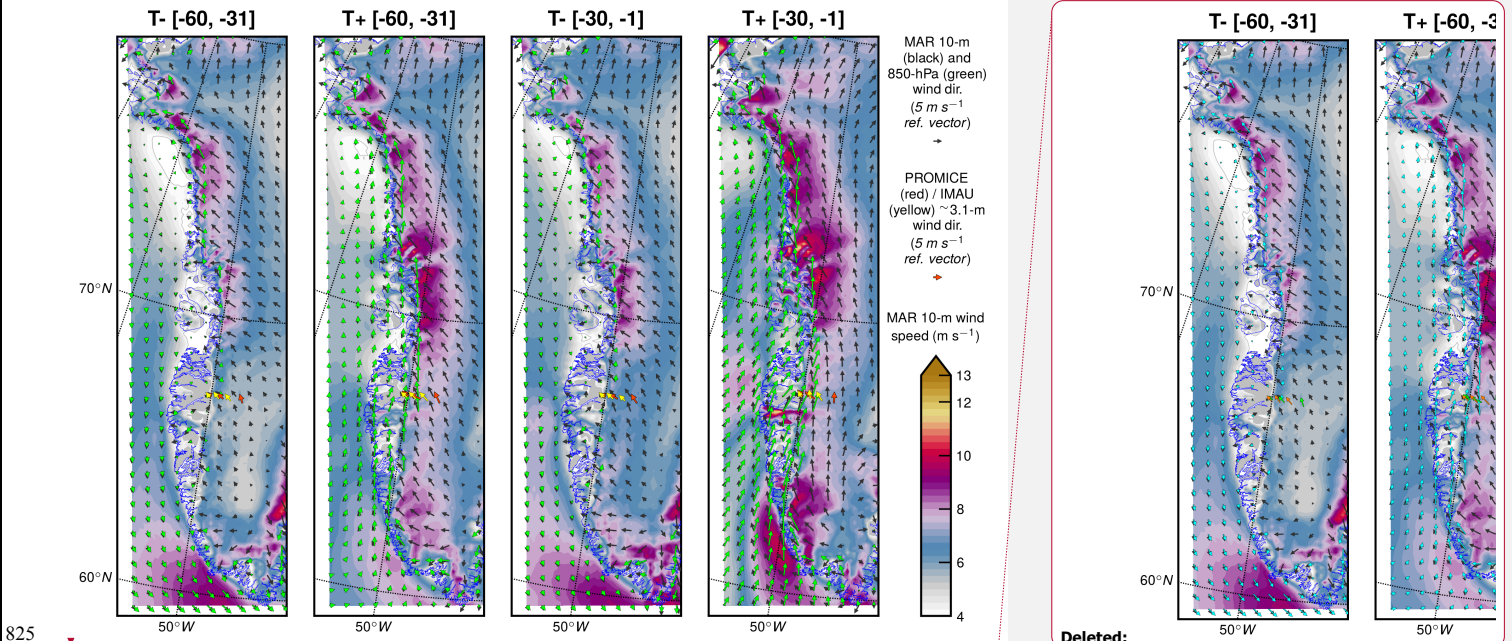
810 **Figure 1.** Study area map with PROMICE and IMAU K-transect sites and adjacent terrestrial DMI stations (Kangerlussuaq (WMO code 4231) and Sisimiut (WMO code 4234)). The inset displays the northwest Atlantic Arctic region with superimposed GrIS topographically-defined boundaries, adopted from Ohmura and Reeh (1991).



815 **Figure 2.** Composites of a) near-surface air temperature, b) wind speed, and c) wind direction for the T+ and T- events at KAN_B preceding Baffin Bay date of sea ice advance (DOA), 2011-2015. Significant differences ($p \leq 0.05$) between T+ and T- composites over similar time windows, are shown by asterisks (*) between the bars. Panel d) shows daily mean wind speed as a function of direction for select, roughly equidistant K-transect PROMICE stations.



820



825

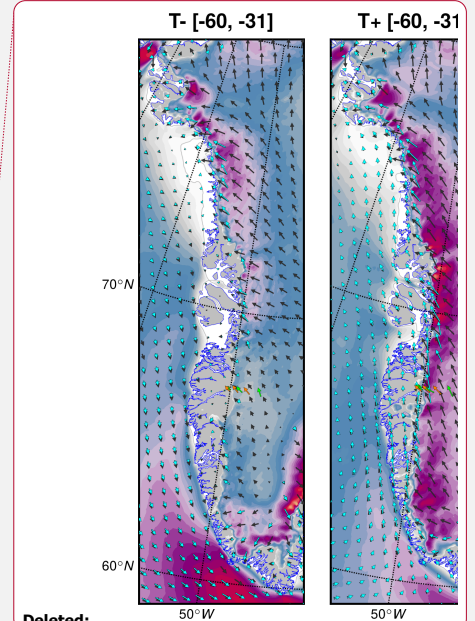
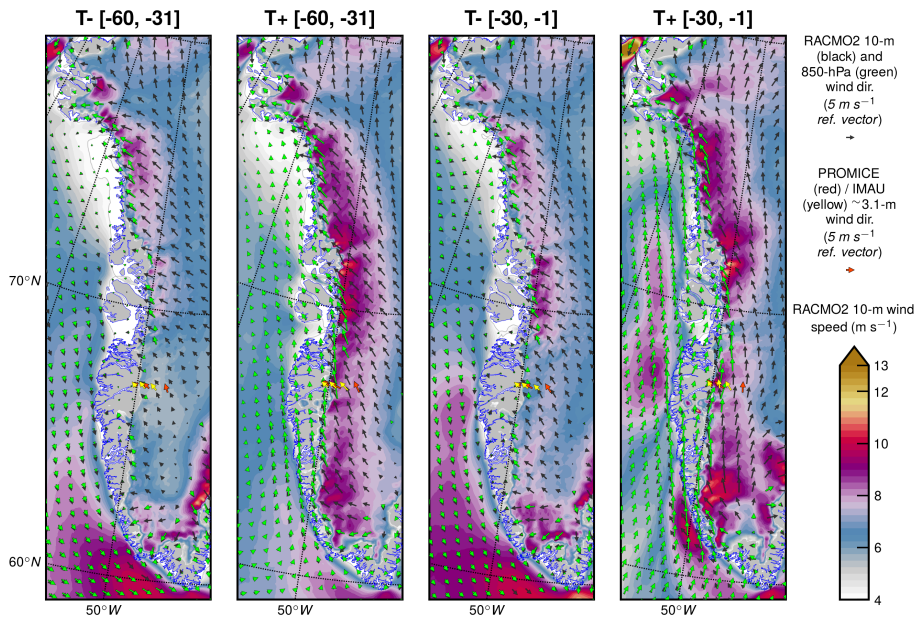
Figure 3. Composites of MAR 10-m (black arrows) and 850 hPa (green arrows) vector winds for the T+ and T- events at KAN_B preceding Baffin Bay date of sea ice advance (DOA), 2011-2015. Wind observations from PROMICE (red) and IMAU (yellow) arrows are overlaid for reference.

Deleted:

Deleted: cyan

Deleted: green arrows

Deleted: orange



835 **Figure 4.** Composites of RACMO2 10-m (black arrows) and 850 hPa (green arrows) vector winds for the T+ and T- events at KAN_B preceding Baffin Bay date of sea ice advance (DOA), 2011-2015 (refer to methods for details). Wind observations from PROMICE (red arrows) and IMAU (yellow arrows) are overlaid for reference.

Deleted: cyan

Deleted: green

Deleted: orange

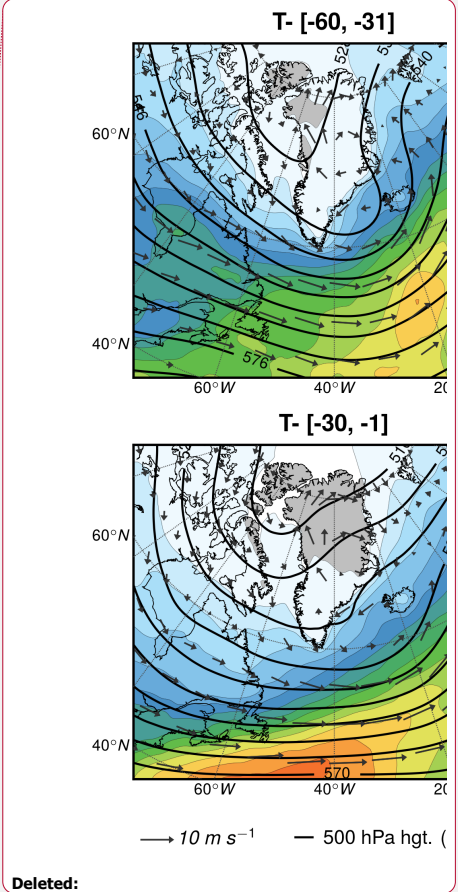
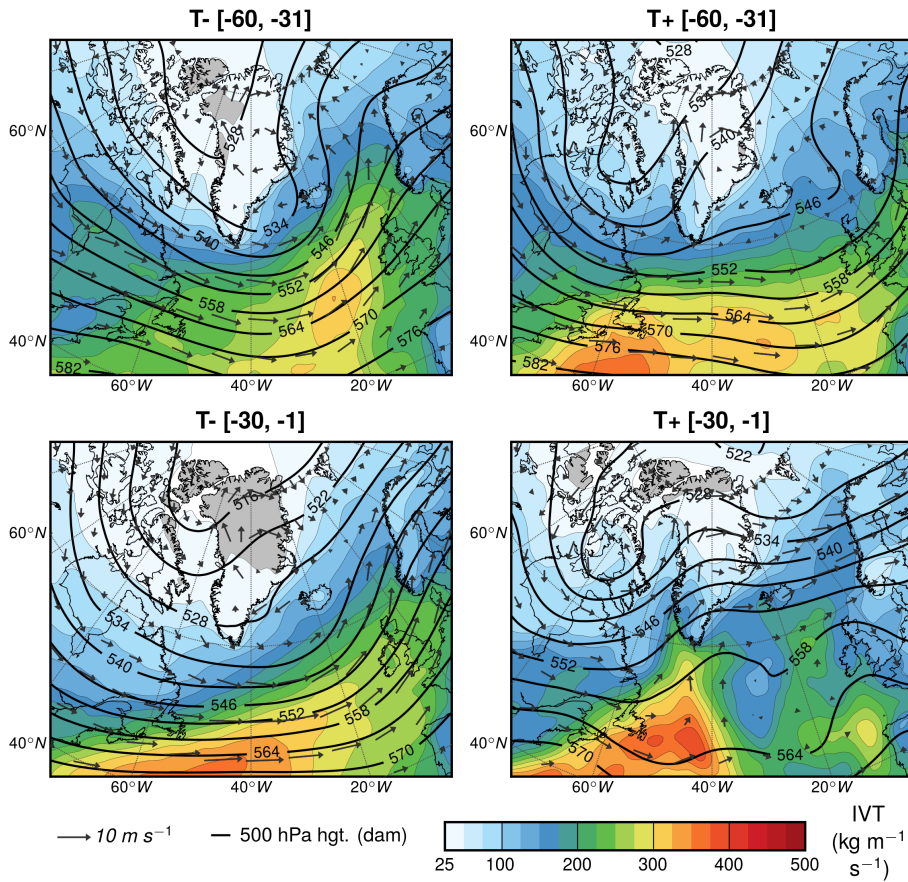
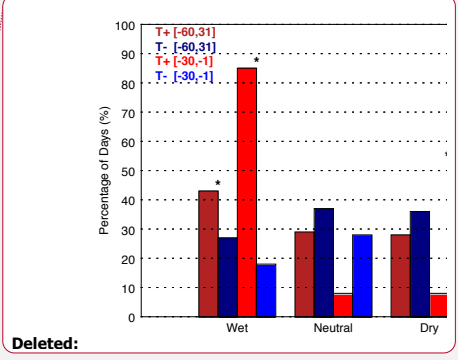
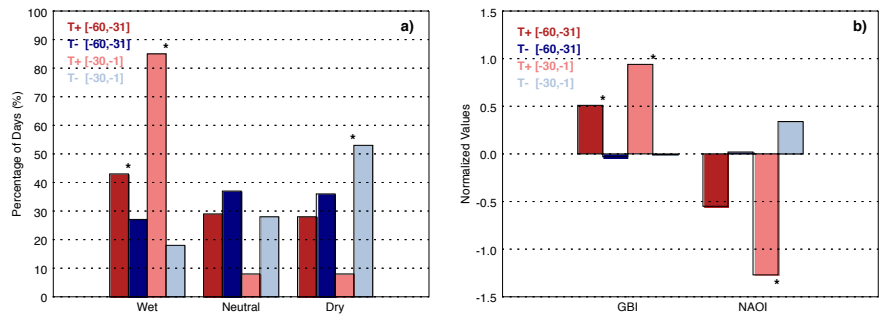


Figure 5. Composite plots of integrated vapor transport (IVT), 1000-700 hPa winds, and 500 hPa GPH from ERA-Interim data for T+ and T- events at KAN_B for the two periods preceding the Baffin Bay date of sea ice advance (DOA).

845



850

Figure 6. Composites of a) self-organizing map (SOM) nodes by wet, neutral and dry types (%) and b) normalized Greenland Blocking Index (GBI) and North Atlantic Oscillation (NAO) values (unitless) for T+ and T- events at KAN_B for the two periods preceding the Baffin Bay date of sea ice advance (DOA). SOM aggregates represent the ratio of each pattern's occurrence to the sum of all patterns for each time period and similarly colored bars sum to 100%. Significant differences ($p \leq 0.05$) between T+ and T- composites over similar time windows are shown by asterisks (*) between the bars.

855

Deleted: by
Deleted: bins

Page 34: [1] Deleted **Microsoft Office User** **3/27/19 11:09:00 AM**

▼.....▲.....◀.....

Page 34: [2] Deleted **Microsoft Office User** **3/27/19 11:18:00 AM**

▼.....

▲.....
Page 34: [3] Formatted **Microsoft Office User** **3/31/19 12:42:00 PM**

Font: Bold

▲.....